UNIVERSIDADE DE SÃO PAULO
Instituto de Ciências Matemáticas e de Computação

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

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Dissertação de Mestrado do Programa de Pós-Graduação em Ciências de Computação e Matemática Computacional (PPG-CCMC)

ICMC USP
SÃO CARLOS

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

Dissertation submitted to the Instituto de Ciências Matemáticas e de Computação – ICMC-USP – in accordance with the requirements of the Computer and Mathematical Sciences Graduate Program, for the degree of Master in Science. *FINAL VERSION*

Concentration Area: Computer Science and Computational Mathematics

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Co-advisor: Prof. Dr. Alexandre Fonseca Brandão

USP – São Carlos
June 2021

Ficha catalográfica elaborada pela Biblioteca Prof. Achille Bassi
e Seção Técnica de Informática, ICMC/USP,
com os dados inseridos pelo(a) autor(a)

M623w

Michelin Jurioli, Mateus
Wearable Device for Immersive Virtual Reality Control and Application in Upper Limbs Motor Rehabilitation / Mateus Michelin Jurioli; orientador Cláudio Fabiano Motta Toledo Toledo; coorientador Alexandre Fonseca Brandão. -- São Carlos, 2021.
88 p.

Tese (Doutorado - Programa de Pós-Graduação em Ciências de Computação e Matemática Computacional) -- Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, 2021.

1. REABILITAÇÃO. 2. REALIDADE VIRTUAL. 3. SENSORES BIOMÉDICOS. I. Toledo, Cláudio Fabiano Motta Toledo, orient. II. Brandão, Alexandre Fonseca, coorient. III. Título.

Bibliotecários responsáveis pela estrutura de catalogação da publicação de acordo com a AACR2:
Gláucia Maria Saia Cristianini - CRB - 8/4938
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Mateus Michelin Jurioli

Dispositivo para rastreamento de movimento aplicado na reabilitação motora de membro superior utilizando Realidade Virtual imersiva

Dissertação apresentada ao Instituto de Ciências Matemáticas e de Computação – ICMC-USP, como parte dos requisitos para obtenção do título de Mestre em Ciências – Ciências de Computação e Matemática Computacional. *VERSÃO REVISADA*

Área de Concentração: Ciências de Computação e Matemática Computacional

Orientador: Prof. Dr. Cláudio Fabiano Motta Toledo
Coorientador: Prof. Dr. Alexandre Fonseca Brandão

USP – São Carlos
Junho de 2021

“People are not disturbed by things,
but by the views they take of them.”
(Epictetus)

RESUMO

JURIOLI, M. M. **Dispositivo para rastreamento de movimento aplicado na reabilitação motora de membro superior utilizando Realidade Virtual imersiva**. 2021. 88 p. Dissertação (Mestrado em Ciências – Ciências de Computação e Matemática Computacional) – Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, São Carlos – SP, 2021.

A Realidade Virtual (RV) tem sido usada em diversas areas como jogos, treinamentos tecnicos, filmes e educação. Além disso ela pode ser empregada em procedimentos de reabilitação motora em pacientes com deficiencia motora, cognitica ou musculo esqueletico provocadas por acidente vascular celebral (AVC). RV combinada com dispositivos de rastreamento de movimento criaram novas possiblidade na aplicação de procedimentos imersivos durante a reabilitação motora dos pacientes. Este procedimentos podem melhoras o saúde e bem-estar dos patientes e até mesmo tornar o processo mais interessante e agradável alem de tornar mais eficientes para os medicos e terapeutas. No entanto, os custos relacionados a essa tecnologia podem ser impraticáveis para uma ampla aplicação no sistema público de saúde. Portanto, este artigo apresenta resultados para um dispositivo de rastreamento de movimento de baixo custo, integrado a ambientes de RV, com o objetivo de proporcionar uma rehabilitação com melhor qualidade aos pacientes com deficiência motora. Este estudo apresenta teste com pacientes e voluntarios para demonstrar a eficácia do sistema desenvolvido.

Palavras-chave: Realidade Virtual, Reabilitação, Dispositivo para rastreamento de moviemnto, Ambiente imersivo.

ABSTRACT

JURIOLI, M. M. **Wearable Device for Immersive Virtual Reality Control and Application in Upper Limbs Motor Rehabilitation**. 2021. 88 p. Dissertação (Mestrado em Ciências – Ciências de Computação e Matemática Computacional) – Instituto de Ciências Matemáticas e de Computação, Universidade de São Paulo, São Carlos – SP, 2021.

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 recover from disabilities provoked by stroke, cognitive deficit, or musculoskeletal problems. VR combined with wearable tracking devices creates new possibilities to apply immersive approaches during motor rehabilitation. This can enhance health care, making treatments more exciting pr pleasant for patients and more effective for therapists. However, the costs related to this technology may be impracticable for a wide application by public health systems. Therefore, this paper introduces results for a low-cost wearable device integrated into VR environments. The objective is to provide a better quality rehabilitation process for most patients with motor disabilities. This research presents test with patients and volunteers to show the system's efficiency

Keywords: Virtual reality, Rehabilitation, Wearable device, Immersive environment, Tracking device.

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LIST OF ABBREVIATIONS AND ACRONYMS

ADL	Activities of Daily Living
AR	Augmented reality
CVR	Cinematic Virtual Reality
DOF	Degrees of Freedom
HMD	Head mounted display
IMU	Inertial Measurement Unit
IR	Infrared radiation
RGS	*Rehabilitation Gaming System*
VRRS	Virtual Reality Rehabilitation System[1]

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[1] <http://khymeia.com/en/products/vrrs/>

LIST OF SYMBOLS

O — Origin point

$P1$ — Generic point in the space

$\overrightarrow{OP}$ — Vector between points O and P

Acc — Accelerometer

$Gyro$ — Gyroscope

Mag — Magnetometer

$op-amp$ — operational amplifier

V_{UTP} — Voltage upper trigger point

V_{LTP} — Voltage lower trigger point

f_c — Critical frequency

m — Mass

$\overrightarrow{V}$ — Velocity V

$\overrightarrow{\Omega_z}$ — Angular rate

$\overrightarrow{F_{Coriolis}}$ — Coriolis Force

$P1$ — Point in the space P1

$P1$ — Point in the space P0

$\overrightarrow{P0P1}$ — Vector between points P0 and P1

Q — Quaternion

ϕ — Rotation in X-xis

θ — Rotation in Y-xis

ψ — Rotation in Z-xis

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Context

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, several areas use VR, such as video games, technical training, movies, and teaching (ALFARO *et al.*, 2019; MATEER, 2017; HUANG *et al.*, 2019; SWEETSER; ROGALEWICZ; LI, 2019). VR is also applied in clinical interventions for rehabilitation processes. There are applications in motor recovery therapies (LAVER *et al.*, 2017; LEVIN; WEISS; KESHNER, 2015; CAMEIRÃO *et al.*, 2011; SVEISTRUP, 2004; SCHULTHEIS; RIZZO, 2001) to help patients recovering from disabilities caused by stroke, cognitive impairment, or musculoskeletal problems. The level of immersion is one of the reasons for using a VR environment to stimulate, e.g., a post-stroke brain, by making the procedures look like a day-to-day activity (LAVER *et al.*, 2017).

The stroke is the third leading cause of disability worldwide (WORLD. . . ,). 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 (MAULDEN *et al.*, 2005). The authors (SHIN; RYU; JANG, 2014) describe that repetitive motions during the physiotherapy sessions can help the rehabilitation process, but it is challenging to keep the patient motivated while doing all repetitions.

VR interaction usually relies on controllers with buttons and joysticks or visual-based controllers such as Kinect. These controllers are not always adaptable to a patient with a downward movement of her/his arm. Thus, a tailor-made wearable device can become necessary to control the objects better 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 exciting and pleasant for patients and more effective for physiotherapists.

The costs related to this technology may be impracticable for a wide application by public health systems. This is the case of the *Sistema Único de Saúde* (SUS) - Unified Health System - in Brazil, which is one of the largest and most complex public health systems in the world. SUS is supposed to provide free procedures ranging from simple care, e.g., blood pressure assessment, to more complex care such as organ transplantation. Thus, VR-based treatments for rehabilitation demanding high-tech and expensive devices can not be affordable by public health systems like SUS.

Therefore, the present Master of Science project proposes an affordable VR-based device useful for public health systems. It has potential to help stroke patients and therapists improve the motor rehabilitation process by taking advantage of VR's immersive experience applied to rehab.

1.2 Gaps and Goals

VR as a complementary therapy to post-stroke rehabilitation is growing significantly in the last few years. Many researchers have applied VR as a non-immersive treatment by using a screen projection in a wall or even a simple monitor to lead the patient to the virtual environment. The simple monitor is often used when some mechanical prototypes are employed to guide the patient's movements through a videogame projected in a monitor (FRISOLI *et al.*, 2007; LO; XIE, 2012; REN; PARK; ZHANG, 2009)

These approaches can effectively improve the rehabilitation process but may not be employing the full power of immersive VR. The immersive VR can change the perspective of reality and space in a healthy person, as the current VR videogames have shown; therefore, it may also modify such view for post-stroke patients. In the virtual environment, the user can make movements that are not possible in the real world, which means that patients with almost no mobility in the arm can see, e.g., the upper limb moving and reaching objects in the VR scenario. Virtual reality technology can improve the brain's plasticity as well as enhance motor learning and rehabilitation process (CHEUNG *et al.*, 2014).

The device to track the patient's movements can be divided into three groups: robotic arms, visual-based tracking, sensor tracking. Robotic arms can get precisely the position of the patient's arm in the space, but the cost of the maintenance and the equipment is an issue of this approach. Visual-based tracking can evaluate the user's arm position based on images such as a webcam. Still, this method starts to fall apart when a therapist needs to help the patient because he/she will enter in the range of the camera, disturbing the tracking, or even losing the track completely. The last one, sensor tracking, is to track the movement based on the inertial sensors such as accelerometer, gyroscope, or magnetometer. This approach presents the problem of accumulate error over time, making the precision unstable.

In the context of this project, we summarize the three main gaps found so far when thinking about VR-base treatments for motor rehabilitation within the context of public health systems:

- **Immersive experience.** There is a demand for more immersive environments instead of employing just projections of the VR environment using monitors.
- **Costs of devices.** The track of movements can demand expensive hardware resources. In the same way, the immersive experience improves by using more expensive VR devices. However, these resources usually cannot be affordable by public health systems.
- **Usefulness of virtual reality versus effectiveness during treatment**. There is always a gap between the use of the VR environment and its effectiveness during motor rehabilitation treatment. Thus, better cooperation between the therapist and the VR development team can fill such a gap, e.g., leading the VR tool to generate valuable data for the therapist.

This project aims to make available a more immersive treatment for patients and affordable for public health systems without compromising the quality of the rehabilitation process. To pursue such a main goal, we will accomplish some other related goals:

- Integration of the VR environment and wearable device. It will allow synchronizing the real world's patient movements with the related interactive parts within the virtual space.
- The integration of the VR environment and wearable device must be done through a framework portable, easy-to-set-up, and handle by the therapist and patient.
- Everything developed must be low-cost.
- The immersive VR environment must be designed for some basic treatment protocols such as reaching objects or cognitive tasks.

1.3 Research Question

The main research question stated by this Master of Science project is:

Can the low-cost and immersive VR-based protocol developed by this project provide a worthwhile experience for patients and valuable data for therapists?

Several types of research evaluate the viability and the effectiveness of VR as a complementary tool for conventional treatment, with most of them handling a non-immersive VR in their protocols. Studies such as (LO; XIE, 2012; LUCA *et al.*, 2018; FRISOLI *et al.*, 2007) use high-cost dedicate equipment for the rehabilitation process. However, it becomes challenging to provide an immersive experience and valuable data from a low-cost device. Thus, we want to address such a research question by proposing an effective VR-based protocol through an affordable device.

CHAPTER

2

CONCEPTS

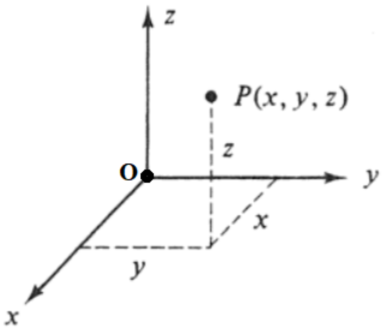
This chapter briefly presents some concepts necessary to understand this research: coordinate systems, virtual reality, game engine, inertial measurement, and noisy filter. The coordinate system explains how the patients' movement can be tracked down from the virtual space. The basic ideas about Virtual Reality (VR) are introduced to clarify what we mean about VR when proposing our VR environment. A game engine, usually employed for game design, was used to develop the VR environment. Thus, the main concepts related to the game engine are introduced. Finally, the presented research developed a wearable device with built-in sensors. Therefore, a brief explanation about how inertial measurement units works is presented as well as the issues related to noise.

2.1 Coordinate System

There are many coordinate systems to represent the same object in a 3D environment. Each one uses sequences of numbers to determine the position of a point in the space. The Cartesian system uses 3 axes with one common point (O) between than and 90 degrees with each axis. The origin point is a reference to determine the coordinate of other points in the space. In this system the point P is determined by $P = (x, y, z)$. The first number (x) represents the distance between the point O in the X-axis; the second number (y) is the distance in the Y-axis between point O and P; the final number (z) shows the distance between the points O and P in the Z-axis. Figure 1 shows the point P in this coordinate system.

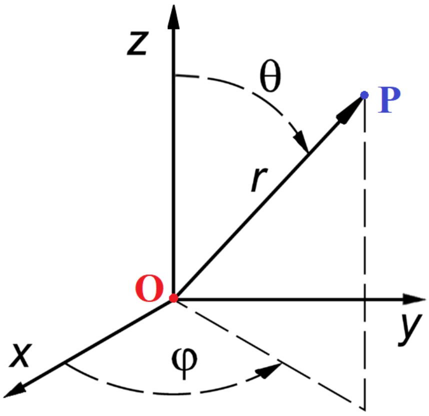
The Spherical system presents the same displacement of the 3 main axes and the point O. The main difference between each coordinate system is how P is represented in the space. The point P is describe as: $P = (r, \theta, \varphi)$. The r number is the linear distance between point O and P; θ is the angle made by the vector $\overrightarrow{OP}$ and the Z-axis. The last number φ is the angle between the projection of the vector $\overrightarrow{OP}$ in the XY-plane and the X-axis. Figure 2 illustrates this coordinate system.

Figure 1 – Cartesian coordinate system



Source: Elaborated by the author.

Figure 2 – Spherical coordinate system



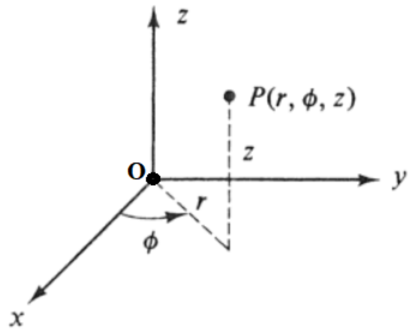
Source: Elaborated by the author.

The cylindrical coordinate system is another way to represent the objects in the three-dimensional space. It uses the same reference axes and origin point (O), but the way to express P is $P = (r, \phi, z)$. In this situation, r represents the distance between origin point (O) and point P's projection in the XY-plane. The second number ϕ is the angle made by the projection of the vector $\overrightarrow{OP}$ and the X-axis. The z number shows the distance of the point P in the Z-axis direction. Figure 3 illustrate this coordinate system.

The device proposes in this project is composed by a IMU with an accelerometer(Acc) a gyroscope (Gyro) and a magnetometer(Mag), which will be better explained in Section 2.4.2. In theory, you can get all the information about the device's position with these sensors. The gyroscope measures the change in the device's angular rate. The accelerometer is a sensor that measures the acceleration of the sensor, including gravity's acceleration. With the magnetometer data we can calculate the direction of gravity. If we subtract the gravity vector to the acceleration, we get the true acceleration of the object. Otherwise, the object is not moving when such subtraction becomes zero.

Let's A be the actual acceleration (Acc value - Mag value), V the velocity in the position

Figure 3 – Cylindrical coordinate system



Source: Elaborated by the author.

zero, and S the position. All of them presenting a component in the Cartesian coordinate system. A, V, and S are functions of time, which means that each one changes during time. If we integrate the acceleration over time, we get the device's velocity, and integrate one more time, and we get the sensor's position. The main issue with this tracking system is the double integral. The actual acceleration (Acc value - Mag value) is not perfect, and there is always an error that is double integrated into the system. For instance, if there is a constant error between Acc and Mag, this constant will be double integrated, and it will become a parabola. The error will become huge in the long run.

To avoid the issue of error accumulation, we work with the device's orientation instead of its position in the space. In this case, it is possible to integrate Gyro's data to get the device's orientation. The main issue with this approach is that the error in orientation data will drift the orientation over time. However, we can fuse the orientation data with accelerometer data (correct to the gravity) and magnetometer data (accurate concerning magnetic north) to fix the drift effect. Therefore, if the user uses orientation made by simply integrating Gyro's data, the device will drift over time because of the error. The device will get an error over time that will be amplified by a t^2 using only the accelerometer to get the 3D position.

As mentioned before, the proposed device uses the orientation in the space instead of the 3D position. It means that the device will lose the translation of the device to the world, but this will not affect the device's usability. The device considers point O (origin) as the user's elbow and the P (tracked point) as the wrist. The better way to use it in the software is to work with the spherical coordinate system. In this case, the r (distance between O and P) is fixed (distance between elbow and wrist). In the other two coordinate systems, the software will need to calculate the components Z every frame with the distance between O and P and the other two components.

2.2 Virtual Reality

Virtual Reality (VR) can be defined as the simulated environment made with computer technology. It makes the illusion of being within a different environment from the real one (STEUER, 1992). This definition generates a lot of interpretations about VR, and, in a broad view of such definition, a computer screen can be considered a VR interface. To reduce the interpretation scope, the authors in (ONYESOLU; EZE, 2011) classified VR systems into three main categories: Non-immersive, semi-immersive, and immersive VR systems.

The first one, non-immersive VR systems, is the least immersive experience. The user handles a standard monitor to access the virtual environment, and the regular input systems such as mouse and keyboard allow interaction with the environment. The second classification, the semi-immersive VR system, tries to increase the user's immersion by expanding the field of view with a large screen projection or using several monitors. The last one, the immersive VR system, is a fully immersive system. The user uses aHead mounted display (HMD) to only see the virtual environment without any contamination of the real world. As the point of views change, the image showed in each eye instantly changes as well. This experience gives the idea of being within the virtual environment without really being physically there.

Thus, VR can be defined by an immersive three-dimensional experience that is assumed as near as possible to reality. This last definition limits the interpretation of the term virtual reality and better defines it. In the 1960s, *Sensorama* (Fig. 4a) was an immersive machine developed to simulate a motorcycle ride through New York. It was a fixed and pre-recorded film without any interaction created by Morton Heilig. In the same decade, the inventor Ivan Sutherland developed a pair of lenses to simulate the real vision as a Head-Mounted-display (Fig. 4b), which was the rise of head-mounted devices like the ones we can see nowadays, such as *Oculus rift* [1], *Sony VR* [2], *HTC VIVE* [3] and other VR1s headsets.

Virtual reality consists of a 3D environment previously modeled and rendered in real-time to the user. For a good VR experience, when the user rotates the head, the screen seen by the user needs to rotate simultaneously. Thus, computer performance becomes an important issue to achieve a satisfactory VR experience. VR needs to be as close as possible to the real world's motion because without accomplishing this aspect, the user can feel some discomfort such as motion sickness (REASON; BRAND, 1975). Nowadays, computer performance is getting better year by year, making many VR applications a reality and reducing the motion sickness effect for users.

Interaction with the virtual world is a tricky part of VR. In the past, it was a passive experience since there was almost no interaction with the virtual environment. With computer processing advances, there are currently several ways to control the virtual world, such as

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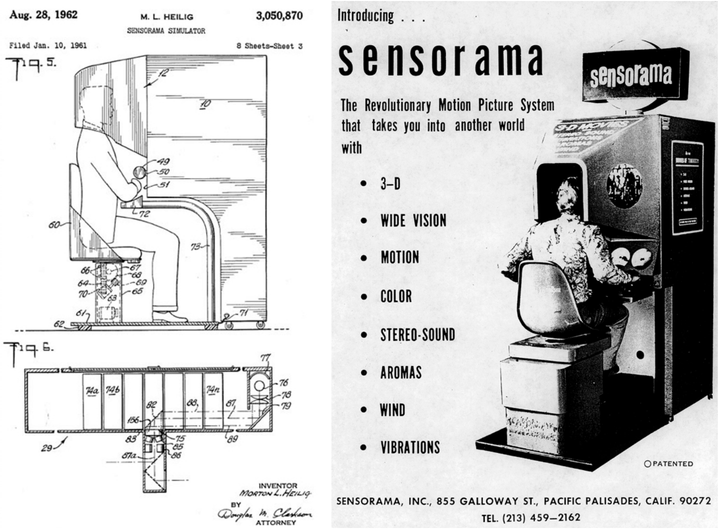
[1] <https://www.oculus.com/?locale=en_US>

[2] <https://www.playstation.com/en-us/explore/playstation-vr/>

[3] <https://www.vive.com/eu/>

Figure 4 – History of Virtual Reality



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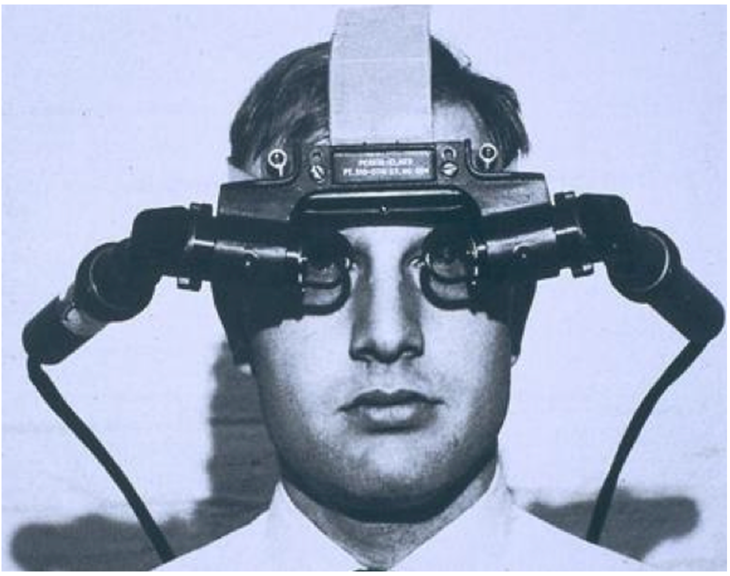
(a) Sensorama



(b) Ivan’s Head-Mounted-display

Oculus, *Playstation VR*, and *SteamVR*. The *Oculus* uses the "constellation" system to track the device’s position. "Constellation" is a group of LED placed following a pattern, where the sensor evaluates the pattern and defines the device’s position in the space. The *Playstation VR* has a simple camera with color tracking to find the controller in the 3D space. The *SteamVR* does not use any camera to track the position of the user. A device placed in the corner of the room sends Infrared radiation (IR), based on the time the IR hit the object and return. The device allows tracking all the room, including the user.

There are several virtual reality applications, for instance, in the medical field, flight simulations, military, video games, cinema, and rehabilitation. Each of these new applications can help to improve the user’s experiences within a specific scenario. In the rehabilitation area, virtual reality has been used as a complementary therapy to conventional procedures(KIPER *et al.*, 2018). This association may optimize the rehabilitation of the users and improve the quality of life in several ways. One issue of VR as a rehabilitation treatment is how the patient interacts with the environment, based on the patient motor disability. For this problem, each research shows a different solution such as exoskeleton robots (PERRY; ROSEN; BURNS, 2007), wearable tracking devices(DIAS *et al.*, 2018), tracking rooms(LUCA *et al.*, 2018).

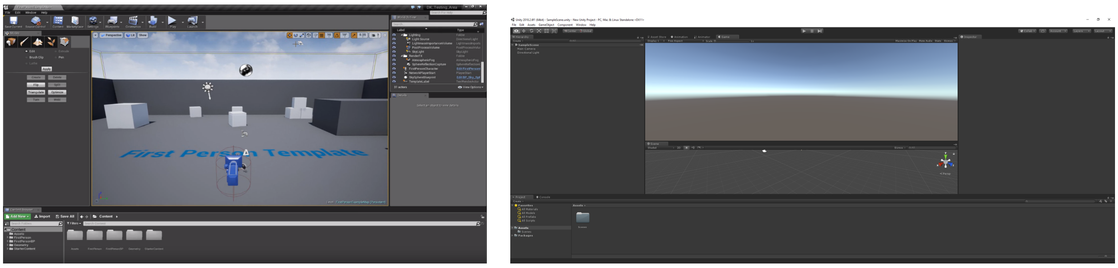
2.3 Game Engine

The expression Game Engine refers to software that helps the developers make the game itself. The concept of the engine divides several aspects of the game development into modules. Each of these modules focuses on a specific area such as:

- **render engine** for rendering 2D and 3D graphics;
- **scene management** to control all the scenes and cameras within the game environment;
- **physics and collision engine** that control the interaction of the objects with the environment;
- **network connection** for management of all external communication between devices.

These modules are a small part of a game engine's complexity, where the developers introduce more content year-by-year (GREGORY, 2017). There are several game engines in the market, each with its particularity for development, such as programming language, interface, and code optimization. For discussion purpose, we will show two of the leading used engines in the market, *Unity*[4] and *Unreal*[5] that are illustrated by Figure 5.

Figure 5 – Engines interface



(a) Unreal Interface

(b) Unity Interface

Source: Elaborated by the author.

The Unreal Engine, released in 1998, is one of the most used engines in cinematography and game development. The platform's primary programming language is C++, but it also

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[4] <https://unity.com/>

[5] <https://www.unrealengine.com/en-US/>

presents an interface to develop a scene without any code. The Unreal Engine can be used by all kinds of developers, small, medium, or larger companies. The Unity Engine started as a Mac OS exclusive game engine in 2005. It expands for several other platforms in a few years, including PlayStation, computers, android OS, Windows OS, and others. Unity presents the ability to render 2D and 3D objects as well as create virtual reality environments. The supported language is C#] and offers a visual interface to the game developer, making a game without the need to code everything by hand.

This project decided by Unity Engine based on the author's knowledge about such an engine. The *Unity* also presents a few assets that will help in the software development and communication with the developed device, e.g., Bluetooth module.

2.4 Hardware

As mentioned, we aim to make available a low-cost virtual reality (VR) device pleasant for patients and affordable to public health systems. The proposed device has two main parts: software and hardware. The first one includes the VR environment itself, which means everything 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 it to the smart-phone. The wearable device has built-in sensors whose related noise must be filtered. Therefore, an explanation about noise and inertial measurement units is presented next.

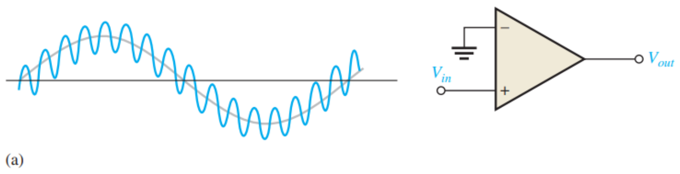
2.4.1 Noise

Noise is an unwanted variation in an electrical signal that affects the circuit (MOTCHENBACHER; CONNELLY, 1993). Nowadays, the circuits are getting smaller, running at a lower voltage and with great accuracy, and these requirements turn the noise issue more relevant (MOTCHENBACHER; CONNELLY, 1993). There are many possibilities for noise sources in electronic devices, such as, noises related to thermal issues in the circuit, imperfections in components, or trail generating high frequencies noise. A noisy power supply can also create more noise in the circuit, where electromagnetic interference is caused by placing multiples pieces of equipment together.

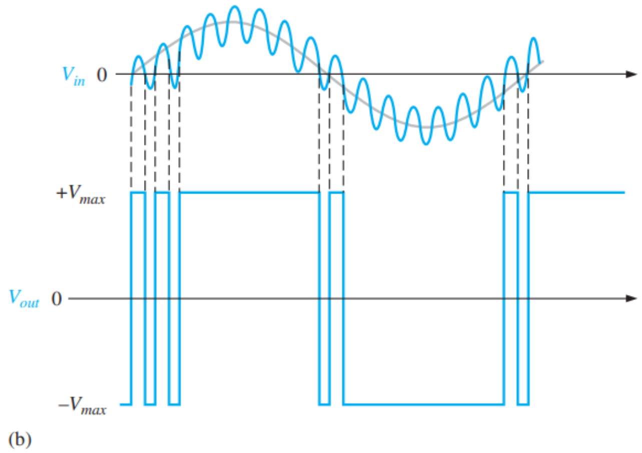
The noise may interfere in the operation of a circuit, changing its outputs. For instance, an operational amplifier (op-amp) that is changing the output based on a low-frequency signal can be highly affected by unwanted high-frequency noise. Figure 6 illustrates this situation.

One of the possible ways to reduce the noise effects is with Hysteresis. Consider the same situation above, an op-amp that changes the output with a low-frequency wave. There is one trigger as an upper bound such that the output is assumed as high, while below the trigger, the output is low. The Hysteresis consists of two triggers, one to change the output to high (V_{UTP}) and one to change the output to low (V_{LTP}) . When the signal wave is above V_{UTP}, the output

Figure 6 – Simulated noise



(a) Sinal

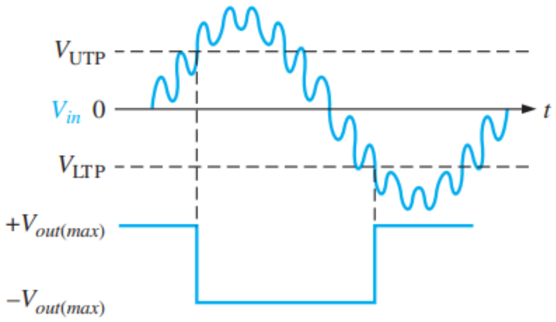


(b) Output

Source: Floyd (2012).

will be high, and when it is below the V_{LTP}, the output will be low. If the signal is in the middle (between V_{UTP} and V_{LTP}) the output stage will not be changed (Fig. 7) (FLOYD, 2012).

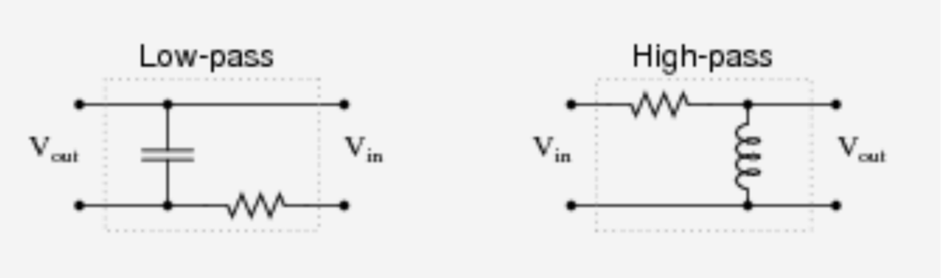
Figure 7 – Hysteresis example



Source: Floyd (2012).

A tool to reduce the impact of noise is a filter, which is a circuit that rejects, attenuates, or lets pass a specific frequency based on its configuration(MOTCHENBACHER; CONNELLY, 1993). There are two types of filters: passive and active ones. The passive filter is composed of passive components such as resistances, capacitors, and inductors. Figure 8 show that the capacitor works as a low-pass filter, while the inductors as a high-pass filter.

Figure 8 – Passive filters



Active components need an external power supply to be part of the circuit, such as an op-amp that can amplify the signal or transistor to control how the energy is flowing in the circuit. When a filter uses one active component, it is called an active filter. According to (MOTCHENBACHER; CONNELLY, 1993), active filter presented several advantages compared to passive filters, for instance, gains provided by the op-amps, it prevents overloading the driving source and is easy to adjust over frequency range without change the response.

The active filter can be divided into four categories: low-pass, high-pass, band-pass, band-stop. All these filters have critical frequencies (f_c)) that established by the design of the circuit. The low-pass filter (fig. 9a) is used to attenuate frequencies above the f_c. The high-pass filter (fig. 9b) is designed to let all frequency above f_c pass and try to reject or attenuate the frequencies below f_c. The band-pass (fig. 9c) and band-stop (fig. 9d) present two f_c (f_{c1} and f_{c2}) because they try to select just the the frequencies between the two f_c. The band-pass reject or attenuate all frequencies that is not in the range between f_{c1} and f_{c2}, and the band-stop reject or attenuate the frequencies inside the same range (between f_{c1} and f_{c2}).

We used a low-pass filter in the proposed device that tracks the patient's arm movement. Thus, there is no movement in the device that will generate a high-frequency wave. All high-frequency waves become noise in the system, and they can be rejected or attenuated by a low-pass filter.

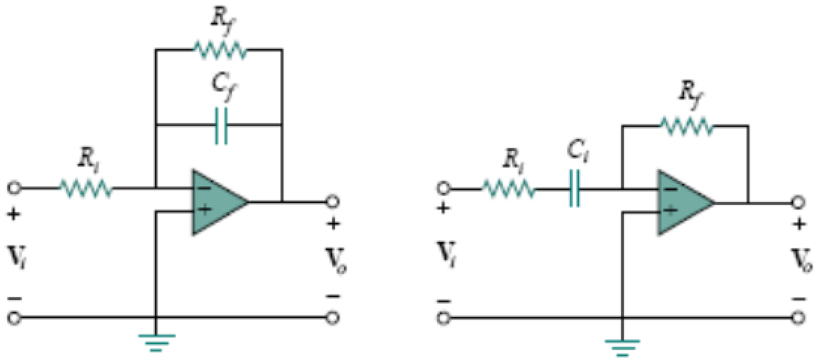
2.4.2 Inertial Measurement Unit

Inertial Measurement Unit is an electronic device that measures orientation, velocity, and gravitational forces. Theses measures are made by components: accelerometer, gyroscopes, and magnetometers(GREWAL; WEILL; ANDREWS, 2007).

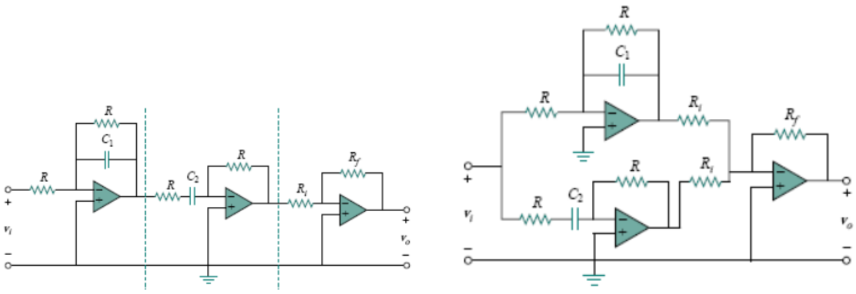
The accelerometer measures the acceleration through the change in the capacitance. There is a mass attached to springs that can move, and there are several fixed plates. The capacitance (C1 and C2) between the mass and the fixed plates are measure; when an acceleration has applied, the capacitance (C1 and C2) changes.

The gyroscope measures the angular rate using the Coriolis effect. The Coriolis effect is a phenomenon that occurs when a mass (m) presents a velocity in a direction ($\overrightarrow{V}$) and the

Figure 9 – Active Filters



(a) Low-pass Filter (b) High-pass Filter



(c) Band-pass Filter (d) Band-stop Filter

Source: Motchenbacher and Connelly (1993).

mass tries to change the angle of the velocity ($\overrightarrow{\Omega_z}$) leading to the force named as Coriolis force ($\overrightarrow{F_{Coriolis}}$). The gyroscope presents a mass that is constantly moving and fixed plates. When an angular rate is applied, the Coriolis forces change the capacitance between the moving mass and the fixed plates.

The magnetometer device measures the magnetic field by the hall effect. The hall effect is the difference in voltage that a magnetic field makes in a conductive plate when a current is passing by.

The device in this project presents an IMU module with all three sensors: accelerometer, gyroscope, and magnetometer. The sensor data are fused to get the orientation of the device.

CHAPTER 3

LITERATURE REVIEW

Video games, technical training, education, movies (MATEER, 2017; HUANG *et al.*, 2019; SEYMOUR *et al.*, 2002; SWEETSER; ROGALEWICZ; LI, 2019) apply Virtual Reality (VR) in their development. In (MATEER, 2017), VR is applied to movies as a Cinematic Virtual Reality (CVR). The CVR is a new approach to how films work by reducing the user's level of control. The user can choose the viewpoint but can not interact with the environment. An application of VR in education is presented by (HUANG *et al.*, 2019), making a comparison with Augmented reality (AR). A total of 109 individuals is divided into two groups: AR and VR group. The study concludes that the VR group presented more information retention, paid more attention to the environment, and enjoyed more than the AR group.

(SEYMOUR *et al.*, 2002) conducted VR training for 16 surgical residents. There are two groups, the experimental group and the control group. The experimental group was training using VR, while the control group with conventional training. After the training period, the residents were evaluated by executing a laparoscopic cholecystectomy procedure. The control group got five times more likely to injure the patient and six times more likely to make some mistake. The author concludes that the VR training improves the surgical residents' performance in laparoscopic cholecystectomy.

VR has been used to build an entertainment environment for videogames. There are currently several games that use the virtual reality as a attractive point for gameplay such as *Beat Saber*[1], *Payday2VR*[2]. *Skyrim VR*[3]. A study comparing a horror gameplay experience through a console system (non-immersive) against virtual reality (immersive one) is reported by (PALLAVICINI *et al.*, 2018). The Resident Evil 7: Biohazard was used as a test platform, and the results described no difference based on the level of difficulty. The anxiety felt by users was the same playing immersive or non-immersive. However, the sense of happiness was

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[1] <https://beatsaber.com/>

[2] <https://www.overkillsoftware.com/payday2-vr/>

[3] <https://elderscrolls.bethesda.net/en/skyrim>

more significant within the VR environment and its meaning within the game environment. (SWEETSER; ROGALEWICZ; LI, 2019) shows the VR used in a video game. They compared the non-VR with VR and concluded that the player got more concentrated in the VR game and considered it less controllable than the non-VR game.

There are also applications of VR in clinical interventions for rehabilitation processes. In recent years, interventions using VR have found applications in complementary therapy for more traditional neurorehabilitation methods (LAVER *et al.*, 2017; LEVIN; WEISS; KESHNER, 2015; CAMEIRÃO *et al.*, 2011; PIRON *et al.*, 2009; ROSE; BROOKS; RIZZO, 2005; SCHULTHEIS; RIZZO, 2001; TUROLLA *et al.*, 2013). However, the effectiveness of using VR as a tool for rehabilitation is still a topic raising discussion among therapist (CAMEIRÃO *et al.*, 2011). 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 (CAMEIRÃO *et al.*, 2010; RAJMOHAN; MOHANDAS, 2007). When stimulated by VR, the Mirror neurons may accelerate the reorganization and functional recovery in post-stroke patients (CARVALHO *et al.*, 2013).

The authors in (SCHULTHEIS; RIZZO, 2001) presented a brief explanation about VR, its applications, and its benefits in rehabilitation. The study evaluates the current stage of VR at the beginning of the century (2001) and concludes that there was a lot of work to improve VR quality. However, the author already suggested that VR could become an accessible device for all rehabilitation therapies. The work in (ROSE; BROOKS; RIZZO, 2005) reports a summary of all brain injuries and how VR can affect rehabilitation. The study evaluated the use of VR in cognitive rehabilitation and memory impairments, attention deficits, and spatial impairments. For all cases, the authors presented studies that may consider VR to improve the recovery compared with traditional methods.

(PIRON *et al.*, 2009) introduced a different approach for rehabilitation, telerehabilitation. A total of 36 patients with upper limb impairment was divided into two groups: control and experimental group; they received the treatment for four weeks. The control group was submitted to conventional physiotherapy in a clinic, while the experimental group underwent the Virtual Reality Rehabilitation (VRRS) at home. VRRS is software developed to generate the VR environment for the treatment. The tracking system for motion is the Polhemus 3Space Fastrack [4], which is attached to a real object and tracks its position. The study concludes that both groups presented improvement in the recovery process, but the telerehabilitation had better motor evaluation performance. This research shows that home rehabilitation can be used as effectively as the conventional one.

In (TUROLLA *et al.*, 2013), the authors used the Virtual Reality Rehabilitation System[5]

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[4] <https://polhemus.com/motion-tracking/all-trackers/fastrak>

[5] <http://khymeia.com/en/products/vrrs/>

(VRRS) with a 3D motion tracking system (Polhemus Liberty[6]). They projected an image for the patient on a wall screen in a study including 376 subjects with post-stroke upper limb disability. They were divided into two groups, the first group received conventional treatment for upper limbs rehabilitation, and the second one received the same treatment and the VR combined. The subjects received 40 sessions of daily treatment for four weeks. The authors concluded that the virtual reality treatment achieves significant improvement comparing to the conventional treatment.

VR-based procedures in stroke patients show relevant improvement in their upper limb performance as reported by (CAMEIRÃO *et al.*, 2011) against traditional treatments. (CAMEIRÃO *et al.*, 2011) used an experimental group of 10 subjects and a control group of 9 patients. They submitted the experimental group to the *Rehabilitation Gaming System* (RGS). The RGS setup consists of a camera that tracks the arm's movements based on color detection. The vision-based tracking system presents a limitation: the therapist cannot help the patients without entering the camera field, interfering in the tracking system.

A review of motor control and motor learning principles is presented in (LEVIN; WEISS; KESHNER, 2015) to discuss how virtual reality treatment can affect motor recovery. The authors discuss the flexibility of virtual reality when adapting to a specific treatment protocol for each patient. The versatility of the virtual world may be its main potential for motor recovery. However, the full potential of VR therapy is still unknown. The authors in (LAVER *et al.*, 2017) updated the Cochrane Review by adding 35 recent studies. The review is about the effectiveness of virtual reality for stroke rehabilitation. They concluded that VR presented statistically significant for arm function rehabilitation as well as to Activities of Daily Living (ADL). On the other hand, there was not enough information to evaluate cognitive function rehabilitation.

(KIPER *et al.*, 2018) reported that using VR as a complement to conventional rehabilitation achieved better results than conventional ones. The study used a control group of 68 patients, under only traditional recovery, and an experimental group under traditional and VR rehabilitation with 68 subjects. The focus of such research was in upper limb rehab, aiming to evaluate both treatments better. The study used a sensing glove to interact with the virtual world projected in the wall. They developed a virtual environment for the patient to make simple motions such as elbow flexion, elbow extension, reaching movement, shoulder flexion.

One of the approaches for upper limb rehabilitation is the use of 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 (LO; XIE, 2012). For instance, Armin III offers six actuated Degrees of Freedom (DOF); in other words, six motors help the user with shoulder movements, elbow, and wrist. Even though the cost of this army is high (comparing to different approaches), the benefits of a robotic army are unique and cannot be seen in any other methods. For instance, if the user has almost no force in the army, he/she

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[6] <https://polhemus.com/motion-tracking/all-trackers/liberty>

needs a therapist to do the movement for him/her, and sometimes helping with more power than the user needs. But with an exoskeleton robot, we can control the same force that the user needs to do to move the arm. In other words, the user can control the robotic arm's movement with his arm's strength even if the force is minimal. The software behind the exoskeleton can measure the patient's pressure and evaluate the recovery of the patient.

(FRISOLI *et al.*, 2007) used the exoskeleton arm with VR treatment to optimize the patient's rehabilitation. This equipment has five rotational joints, four of them actuated, representing almost 70% of a range of motion made by a healthy subject. Virtual reality is used as a projection of an environment in a wall in front of the patient. The patients were asked to perform several tasks, make a circular trajectory, or move through a 3D space by pointing in the right direction. Exoskeleton robots present several advantages but also disadvantages. As mentioned, one of the main benefits is that a user with almost no force in the arm can manipulate the equipment and finish the tasks in the VR environment. On the other hand, the equipment needs to be fixed in a room specifically for this application. The exoskeleton robot usually demands a high cost of acquiring and maintenance.

(MACIEJASZ *et al.*, 2014) presents a survey on robotic equipment for upper limb rehabilitation. There are devices where the user needs to have motion/force in the arm to control the equipment, such as *InMotionARM*(KREBS *et al.*, 2004). Some machines make all the patient's movement; it is a passive motion stimulation such as the *NeReBot*(ROSATI; GALLINA; MASIERO, 2007). The survey reports other differences in the equipment, where there are cable driving machines as well as direct motor driving equipment as shown in the *ArmeoPower*[7]. Finally, devices without any motor or actuators only compensate gravity and facilitate arm movement, such as the robot developed by (PARK *et al.*, 2016).

The authors in (ANDRADE *et al.*, 2018) develop a serious game system for rehabilitation of patients with pathologies such as stroke and spinal cord injuries. Two evolutionary algorithms (EAs) adjust the dynamic difficulty based on the patient's limitations. The serious game runs from data input from a device developed for active and passive therapy, allowing flexion/extension, adduction/abduction, or pronation/supination. Results from simulations show that EAs adjust the game's parameter of difficulty properly, and clinical tests will be done as future work. Grasp and Upper-Limb Motion Sensor (GULM Sensor) is described in (APPEL *et al.*, 2018) for upper limb rehabilitation with hand function assessment. A vision system takes images of the hands reaching an object, and an IMU sends accelerations and angular movements. A total of four patients with stroke episodes used GULM for ten days during three hours. The proposed sensor returned measures from which some relevant Spatio-temporal patterns arose. The work in (PERISSINI *et al.*, 2019) improves the vision module of GULM sensor by a hand segmentation approach. An omnidirectional vision system obtains kinematic data by catching images from grasp movement. Segmentation methods are compared from a data set with 102 images, and the results indicate a

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[7] <https://www.hocoma.com/solutions/armeo-power/>

relevant rate for segmentation performance.

The study conducted in (LUCA *et al.*, 2018) shows the effectiveness of VR training in motor performance and cognitive recovery of post-stroke patients. The proposed solution is to combine the BTs-Nirvana[8] device with the rehabilitation treatment. The results reported that VR promotes better recovery than conventional rehabilitation protocols. Still, the device is a high cost and needs to be implemented in a specific space for the equipment. The work in (DIAS *et al.*, 2018) presents a device to control a virtual reality environment for lower limbs. The device has a sonar with a gyroscope/accelerometer to track the leg's position, used for gesture control. The movement followed by the device is translated into action within a virtual city. The city counts with autonomous cars and crosswalks to simulate a natural environment. The aim is to facilitate the patient's immersion during the treatment.

(BRUCKHEIMER; HOUNSELL; SOARES, 2011) developed a serious game for rehabilitation for upper limbs based on webcam. This game shows the camera pointed at the patient and add a layer in from of it. The added layer presents a grid with falling water drops from the top of the screen. The patient needs to reach the water drop before it reaches the bottom of the screen. The evaluation is based on how fast the patient can get these water drops. (SOARES *et al.*, 2014) evaluate this software with 36 patients divided into control and experimental group. Each patient of the experimental group performed 20 sessions between 15 to 30 minutes of the developed game. After this, the researchers observed an improvement in the upper limb range of motion of the experimental group's shoulder and elbow. That's why they concluded that the VR treatment brought benefits comparing to the conventional rehabilitation methods.

The authors in (MAGGIO *et al.*, 2019) report that VR technology is progressing year-by-year, becoming a useful tool to improve the recovery of the patient's cognitive function. They reported improvements achieved in the cognitive domains of patients using VR as an additional treatment. The improvements are based on the results reported from eight clinical studies. For instance, the studies conducted by (RUSSO *et al.*, 2017) and (LEWIS; ROSIE, 2012) show that VR therapy can motivate and be more attractive to the patients. (FONSECA; SILVA; PINTO, 2017) shows improvements in balance rehabilitation with the VR treatment for post-stroke patients.

In the study made by (LEE *et al.*, 2018), VR therapy was used with functional electrical stimulation (FES) to evaluate the benefit of VR in the rehabilitation of upper limbs. The authors conclude that the VR stimulation associated with FES presented better results than FES alone. The conclusion was based on 41 patients divided into a control group and an experimental group. (BOHIL; ALICEA; BIOCCA, 2011) stated that VR could engage and motivate patients in the rehabilitation process by bringing personal data to the environment, such as a personal photo or an engaging activity for the patient. The rehabilitation process requires repetitive tasks, persistence, and consistency; that is why the patient must be motivated and engage in the treatment through

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[8] <https://www.btsbioengineering.com/nirvana/>

more personal and related scenarios.

The interaction between the user and the virtual environment can occur in several ways. It happens from complete passive interaction (the user only observes the environment) to interactive controllers (the user applies controllers to interact with the environment). The VR treatment with an interactive approach has more potential to recover motor functions (BOHIL; ALICEA; BIOCCA, 2011). VR can manipulate the aspects of the real world: space, location, forms, or objects. These kinds of manipulation might increase the neural reorganization (CHEUNG *et al.*, 2014). The illusion of being in a different situation, interacting with the virtual world, may stimulate new brain connections and improve neuroplasticity. Patients without the upper limb's movements start to degenerate a few links in the brain related to the arm's movement. However, (KAKEI; HOFFMAN; STRICK, 2003) concludes that the use of VR with an imaginary arm moving can improve the neural reorganization and may also improve the patient's quality of life.

Several studies concluded that the VR used as a complementary to the traditional treatment could optimize the rehabilitation of a post-stroke patient(LEE *et al.*, 2018; KIPER *et al.*, 2018; TUROLLA *et al.*, 2013; LUCA *et al.*, 2018). The main issue of VR therapy is the cost of the devices to perform the interaction. A high-cost device with high-cost maintenance becomes unfeasible for the large use of this technology. This project approaches such a problem by introducing a low-cost VR procedure with viability to be used in the public health system such as SUS. Table 1 compares our proposal with some of the related works reported.

Table 1 – Works comparison

Research	**Type**	**Evaluation with Patients**	**Low-cost**
(PIRON *et al.*, 2009)	Vision - VRRS	36	-
(CAMEIRÃO *et al.*, 2010)	Vision - RGS	9	Y
(TUROLLA *et al.*, 2013)	Vision - VRRS	-	-
(SOARES *et al.*, 2014)	Vision - D2R2	36	Y
(KIPER *et al.*, 2018)	Vision - VRRS	136	-
(LUCA *et al.*, 2018)	Vision - BTsNirvana	12	-
(DIAS *et al.*, 2018)	Sonar / Inertial sensor	-	Y
(APPEL *et al.*, 2018)	Camera/Inertial sensor	4	-

We compare the most closely related works based on research type, evaluation with patients, and low-cost devices. In the assessment with patients, we indicate if it happens by showing the number of patients. In the low-cost columns, we identify those work that has a low-cost system. The visual-based approach is one of the lowest costs and can be used practically everywhere with just a camera. The inertial sensor can be used with a therapist's help without compromising the tracking system. The research in (CAMEIRÃO *et al.*, 2011) and (APPEL *et al.*, 2018) propose an approach with inertial sensors trying to synchronize better moves made by patients. There are 6 out of 8 works in Table 1 evaluating the proposed systems with patients, which is mandatory for a better validation of this type of research. We follow some of these features by fusing VR technology with an interactive world, proposing a low-cost device, and validating it with clinical tests.

CHAPTER 4

METHODOLOGY

This device's development has the collaboration of specialist therapists and meets the need for rehabilitation procedures defined by them. The main objective is to translate the patient's movement into the virtual environment, amplifying or decreasing her/his sensitivity based on the rehabilitation process.

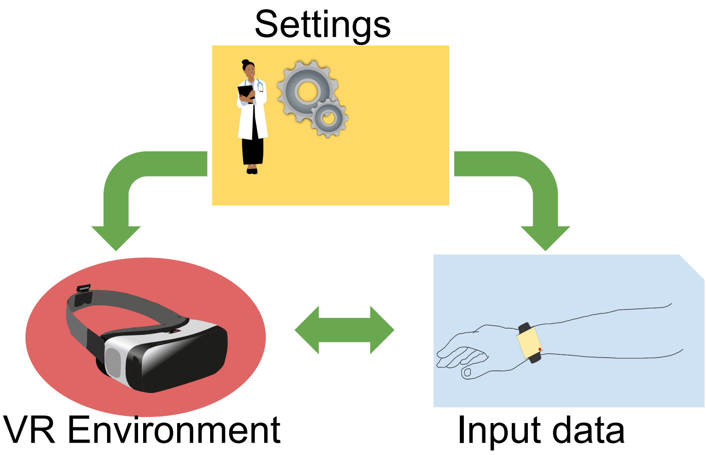
One of the device's requests was that the therapist could move the user's hand without interfering with the tracking system. This requirement meant that a visual-based tracking system became almost impossible since there was overlap between the therapist and the patient's arms. The device and the related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

The proposed device has two main parts: hardware and software. The hardware is the wearable device that will track the patient's motion and send them to the smartphone. The software includes the VR environment itself, which means everything the patient will see on the smartphone with the VR headset. We integrate the VR environment into a wearable device that controls interactive parts of the virtual space. The integration of the VR headset (with a smartphone) and the wearable device becomes portable and easy to set up and handle. As everything developed must be low cost, we design the VR environments to run on various smartphone models.

Figure 10 gives an overview of the proposed system, which has three main modules: Settings, VR Environment and Data Input. The therapist can control all the virtual environment settings: number of pieces in the puzzle, sensitivity, hitbox, image, and other options. The module Settings is responsible for allowing the therapist to set all parameters. Once everything is set, the VR Environment builds the gameplay based on the therapist's choices. After the system creates the VR environment, the puzzle asks the patient to press the hardware device's red button on his arm to start the game. When beginning the puzzle, the smartphone communicates by Bluetooth with the hardware to get all the movement information and control the gameplay simultaneously.

Thus, the Input Data module is in charge of establishing such communication.

Figure 10 – System overview

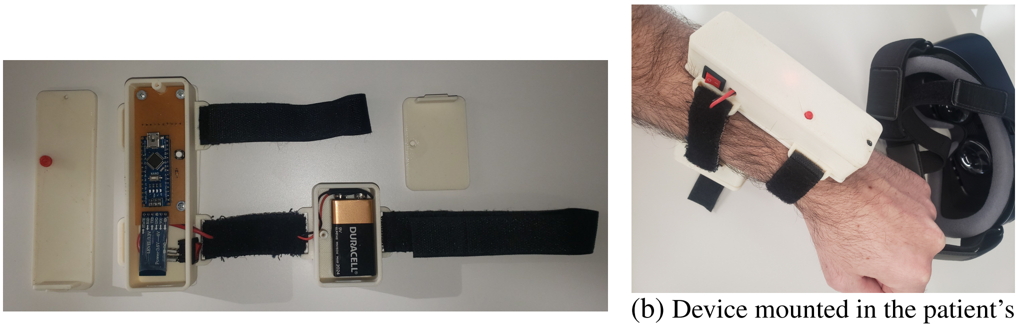


Source: Elaborated by the author.

4.1 Device's overview

As a device to be used by the therapist in the rehabilitation processes, it has to be simple, practical, and versatile to reach all patient treatment complexity. The prototype encapsulates 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.11.

Figure 11 – Proposed device



(a) Disassembled device

(b) Device mounted in the patient's arm

Source: Elaborated by the author.

The second prototype has a new layout with a rechargeable battery (3.7V) and smaller circuits, and 3D printed box. To accept a 3.7V power supply, we redesigned all the previous circuits and added a charging circuit for the battery (Fig.12). The sensor works with 60Hz of data acquisition.

Figure 12 – Final Device

Source: Elaborated by the author.

The system uses a smartphone as a screen to the patient get an immersive VR experience. The sensor is attached to the patient's arms to interact with the VR environment. This system provides immersive to the user as well control of his hand to control the virtual world as well as easy access to therapist help if necessary.

In summary, the system was developed to be easy to use by the therapist, simple for the patient to control the VR environment, versatile in relation to the software used in the smartphone. All these features were developed in collaboration with therapists to optimize each part of the development process.

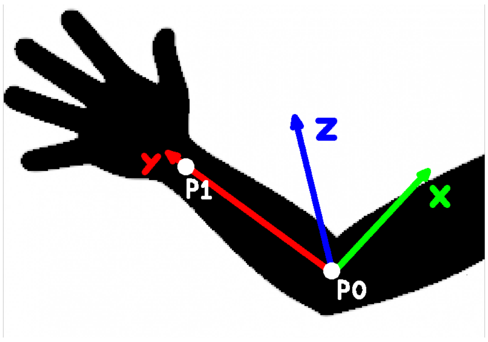
4.2 Device's design

This project proposes a device that tracks the arm using a spherical coordinate system based on such requirements. In other words, the device tracks a point in the user's wrist, P1 (Figure 13, based on another fixed point in the elbow, P0 . Compering with figure 2 the r value is the distance between the point elbow and wrist (P0 and P1). In contrast, 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 it can be seen in Fig 13.

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. 13. 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.

The gyroscope measures the angular velocity of the device. The gyro's data can be written as a sum of cosine in the frequency domain (or sine). The device needs to measure the device's orientation in space; for this, it integrates the gyro's data over time. But this integral

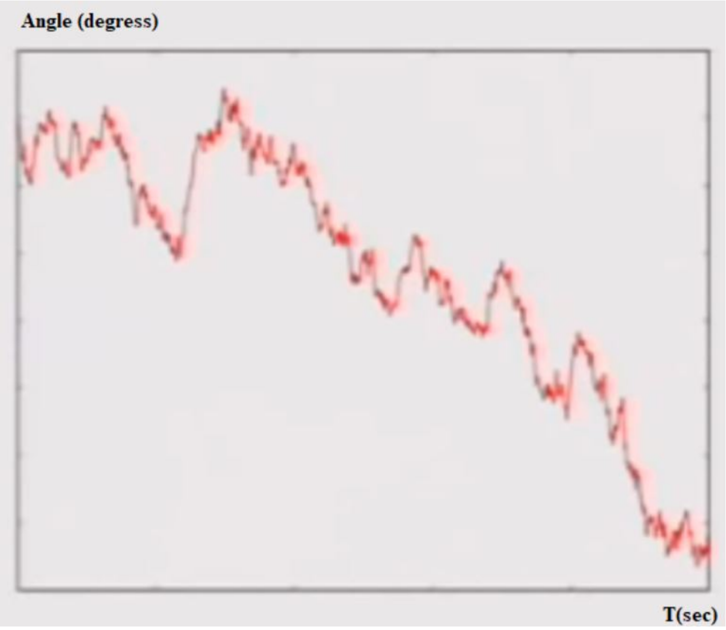
Figure 13 – Device's Coordinate System



Source: Elaborated by the author.

generates drift (Figure 14). The drift is caused by the cummulative error from the gyro's integral. To simplify the explanation, we will consider that the gyro is a single cosine, assuming the integral given by equation 4.1.

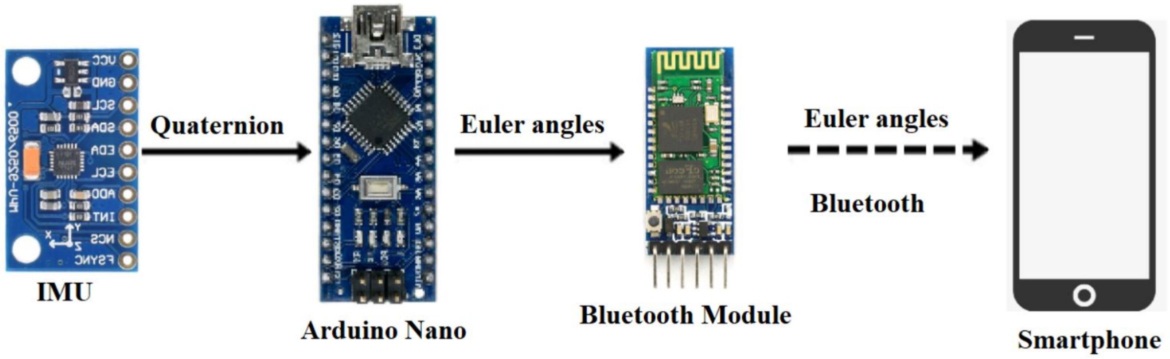
Figure 14 – Drift behaviour



$$\int \cos(2\pi f t)dt = \frac{\sin(2\pi f t)}{2\pi f} + C \tag{4.1}$$

The integral of $\cos(2\pi f)$ generates a $1/(2\pi f)$. The integral works as a low pass filter, in other words, high frequencies are attenuated and low frequencies amplified, generating drift over time. To perform better, we need to fuse data between sensors to improve precision. We integrate the gyroscope and use the linear acceleration to correct the drift over time. The sensor fusion needs to be done as close as possible to the sensor because of the process's delta time. That's why we use the Digital Motion Processor (DMP) on the IMU to calculate all the sensor fusion of the project. Figure 15 shows the flow of the sensor's data.

Figure 15 – Flow of sensor's data



Source: Elaborated by the author.

Arduino Nano microcontroller was used with one IMU (MPU-9250) and a Bluetooth module (HC-05) to develop the device. The microcontroller, powered by a 9V battery and all other components by the microcontroller. The IMU sensor is responsible for getting the gyroscope, accelerometer, and magnetometer data. The MPU-9250 uses the Digital Motion Processor (DMP) to fuse this data and reduce each sensor's errors.

A quaternion (Q) returns the result of this fusion, given by equation 4.2, to describe the orientation of an object in a 3D space.

$$Q = q_0 + q_1 i + q_2 j + q_3 k = (q_0, q_1, q_2, q_3) \tag{4.2}$$

Source: Anton and Rorres (2001).

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

$$\begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix} = \begin{bmatrix} \arctan \frac{2(q_0 q_1 + q_2 q_3)}{1 - 2(q_1^2 + q_2^2)} \\ \arcsin(2(q_0 q_2 - q_3 q_1)) \\ \arctan \frac{2(q_0 q_3 + q_1 q_2)}{1 - 2(q_2^2 + q_3^2)} \end{bmatrix} \tag{4.3}$$

Source: Anton and Rorres (2001).

These angles represent the angles of the patient's wrist 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 processing, it is sent to the smartphone (via Bluetooth module) allowing the user to control the VR environment. The devices present a switch to power on and a button to reset the VR environment's center position as explained in section 4.1.

4.3 Software: Jigsaw Puzzle

The software's main focus was to assist therapists and patients, based on the type of movements done by the patients following the therapist's commands. VR jigsaw puzzle was the game developed to keep a satisfactory level of immersion for patients. Discussions with some therapists supported our decision about this type of game. The game was developed using the Unity3D engine (UNITY3D,) to run in smartphones. We use a smartphone with a headset to simulate the immersive environment, but the proposed puzzle must run in low-cost smartphone models. At this step of our research project, the software can run from any device with Android 5.1 (or higher), quad-core processor, 1.3GHz and 2GB of RAM.

4.3.1 Puzzle Settings

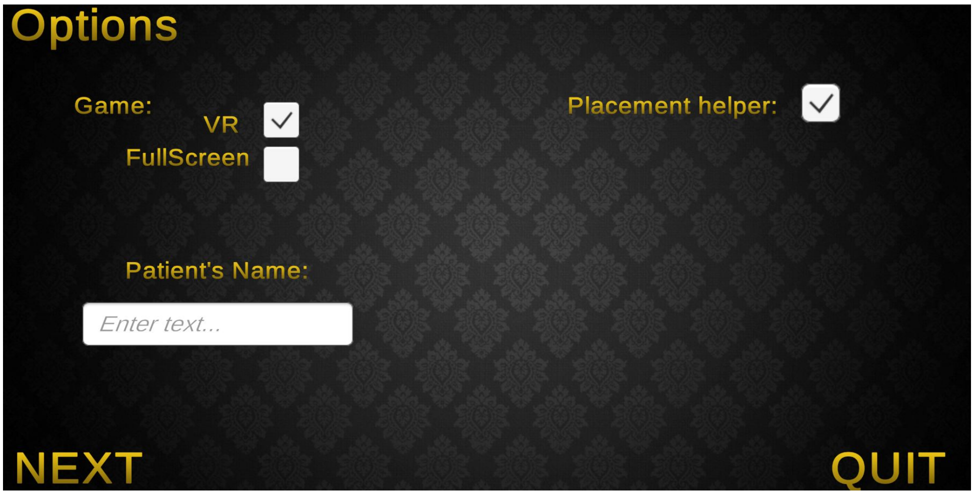
The jigsaw puzzle presents a few settings as shown by Fig. 16. The therapist can use these settings to optimize the VR experience during the recovery process. The parameter settings implemented until now are game type, patient's name, placement helper, level of sensitivity, the number of pieces in the puzzle, in which arm the patient will hold the device, hitbox and image selection.

The setting of parameters will define the patient's experience playing the game. If the therapist chose a VR approach, the patient needs to use a VR headset to play the game, but if the therapist prefers to show the game through a monitor, she/he can select the "fullscreen" option. Another essential feature is the "patient's name", where we recommend the patients' initial for a matter of privacy. The name will be the key to saving data from the game in a database for future evaluation of the patient evolution. The last option in the First Menu (Fig. 16a) is the placement helper. It is a helper for the user during the game, and can be adjusted ON or OFF. If the ON option is selected, the game will help by showing the patient's right position to place the puzzle's piece. This option is essential to evaluate the cognitive function of the patient. In some situations, the therapist prefers to train only the motion, turning this setting ON. On the other hand, with patients without huge motion compromise, the therapist can simultaneously develop the arm's moves and cognition.

The parameter level of sensitivity represents how the real motion will behavior in the VR environment. It is a number set by the therapist between 0 to 100. For instance, if the sensitivity is set 100, a small motion in the real-world will be more significant in the VR puzzle. On the other hand, this effect is less amplified by setting higher values for sensitivity. The therapist also decides the number of pieces that the patient will assemble to complete the puzzle. The current possibilities are to cut the image from 2x2 to 4x4 pieces.

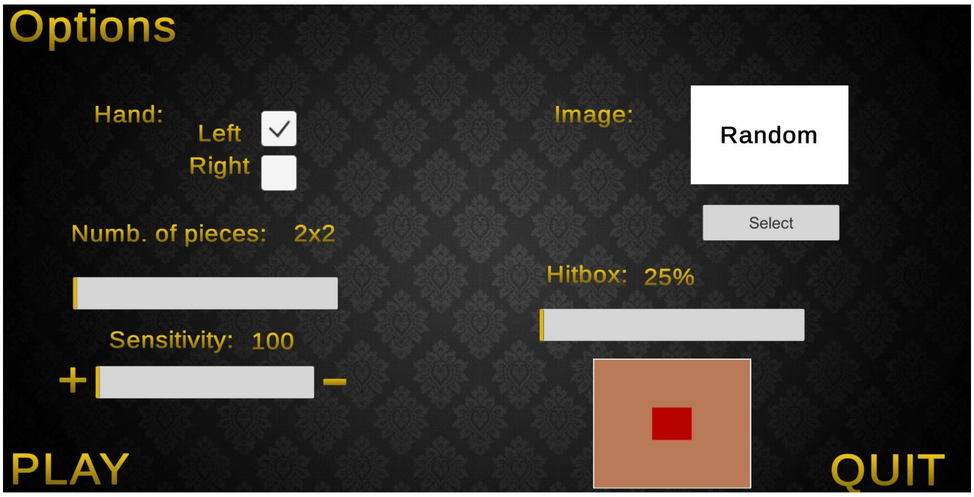
The software works with one patient arm being used in the VR environment to control every interaction with the puzzle. Thus, the therapist must set whether the patient will move the puzzle pieces using the left or right hand. The precision reached by the user when catching and

Figure 16 – Puzzle setting screen



Game:
VR ☑
FullScreen ☐
Placement helper: ☑
Patient's Name:
Enter text...

(a) First Menu



Hand:
Left ☑
Right ☐
Image:
Numb. of pieces: 2x2
Hitbox: 25%
Sensitivity: 100

(b) Main Menu

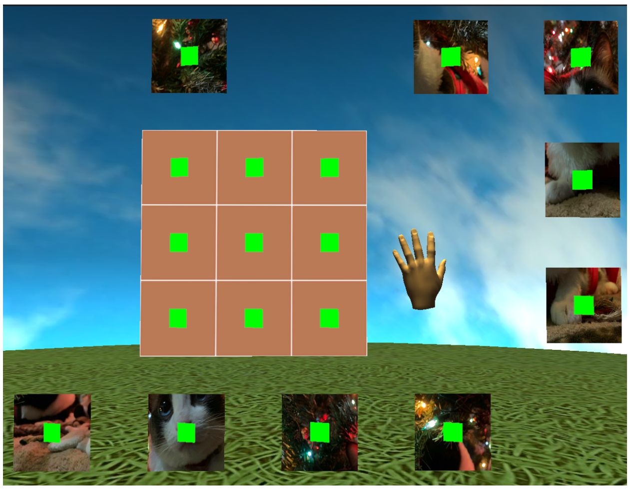
Source: Elaborated by the author.

placing the pieces is another relevant approached feature. Based on this demand, we developed a hitbox sliding bar on the menu. The hitbox tells us how near to the center of the piece the user must be closed enough to pick the piece. The same idea applies to place the piece in the correct position.

For instance, the orange square in Fig.16b 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 it, she/he needs to put iin the right position. This position has the same hitbox as the piece; in other words, the user needs to get inside the hitbox area to put the puzzle's piece in place. Fig.17 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.16b gives the therapists the ability to control the size of the hitbox to fit the patient's needs. Thus, the therapist

Figure 17 – Hitbox



Source: Elaborated by the author.

can adjust the hitbox, becoming more or less challenging to pick up or to position the pieces as illustrated in Fig.18.

Figure 18 – Hitbox settings

(a) High precision - small hitbox (b) Low precision - large hitbox

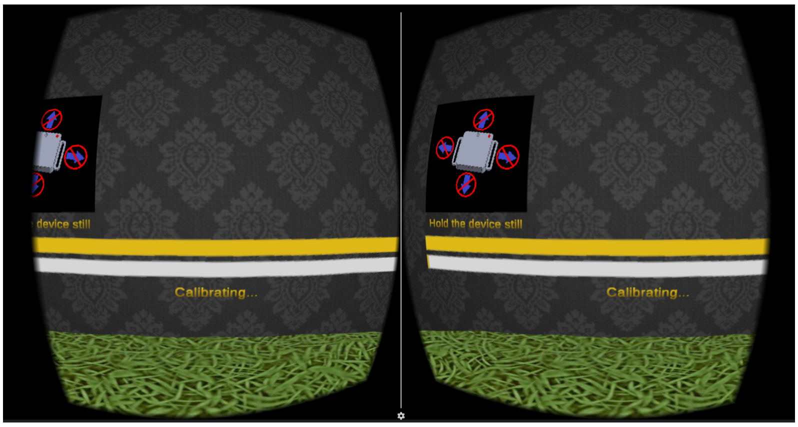
Source: Elaborated by the author.

The patient’s motivation is an essential part of the rehabilitation process. Thus, the puzzle accepts different images, including personal ones provided by the patient.

4.3.2 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 therapist can place the VR headset in the patient while the calibration is happening. Fig.19 shows the calibration processes screen.

Figure 19 – Calibration screen

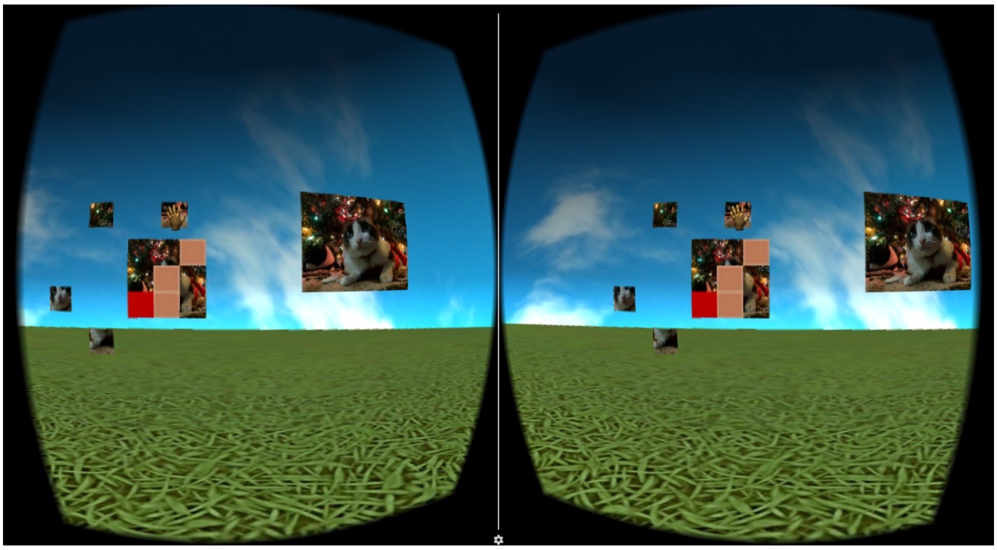


Source: Elaborated by the author.

After 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 virtual environment's center. The patient will need to have some space in the natural environment to move the arm in all directions (up, down, left, and right).

Once the game started, the user only has to complete the virtual puzzle. When the user gets the piece, the software helps him find the piece's correct position showing a red square in the respective area (Fig. 20). The system will also offer a complete picture in the upper right corner to help the patient solve the puzzle.

Figure 20 – Jigsaw Puzzle



Source: Elaborated by the author.

The software's relevant data is stored during the patient gameplay to evaluate his/her rehabilitation process in a folder with the name and date. The data stored is when 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 and the data from accelerometer and gyroscope. These data allow quantifying the movements performed by the patient during the execution of the puzzle.

CHAPTER

5

RESULTS

This chapter will report the results obtained by this project, taking into account four main aspects. First, we reported our finds evaluating the functioning of the device' sensors, where results about its precision and robustness are described. Second, healthy volunteers evaluated the device to give us some insights into how it behaviors with people without any motion problem. Next, three patients used the device with a therapist's guidance, which allows us to have some useful feedback about system performance. Finally, four therapists give us their opinions and remarks about the proposed device while a useful rehabilitation tool.

5.1 Functioning of the Device' Sensors

We evaluate the precision of the sensors within a short and long period without movements. First, the device is holding still for 3 minutes to collect data. The relevant data gathered is shown in Table 2. As expected, even without any movement, there is a minimum but acceptable deviation, near-zero degrees, in the position setting.

Table 2 – 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°

Source: Research data.

The standard deviation must be around zero; otherwise, the user will notice hand movement over time. Thus, the maximum and minimum values in Table 2 need to be close to zero to achieve the desired accuracy without a spike in the movement.

The next test evaluates the robustness of such a sensor's accuracy in the long run, verifying the hardware's reliability. Thus, the device was in a non-movement stage for 1 hour and, after this time, the errors were evaluated, as we can see in Table 3:

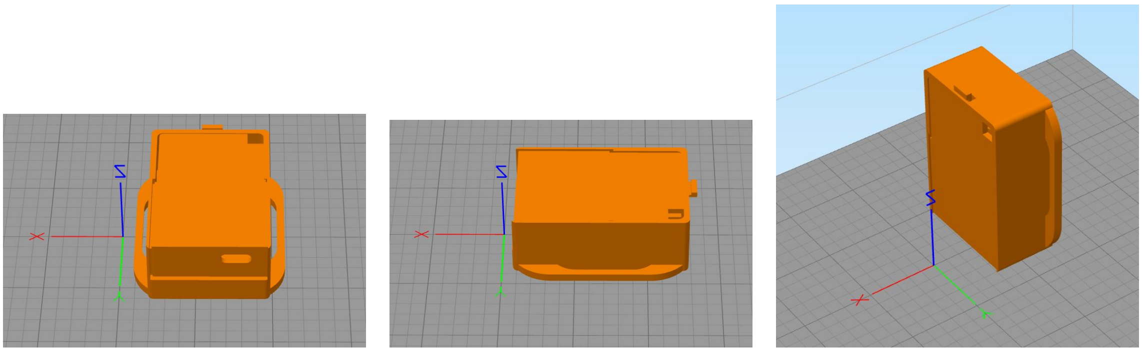
Table 3 – Device's reliability in a long run

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°

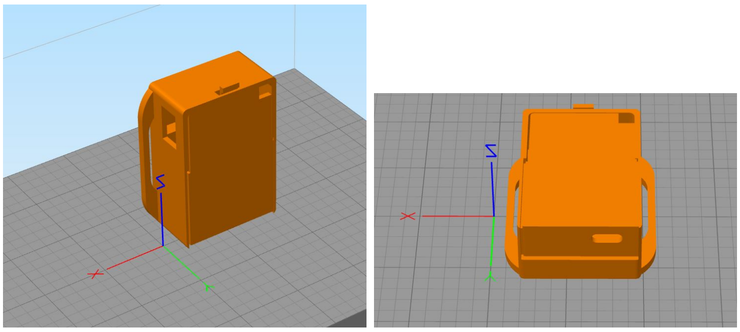
Source: Research data.

Comparing Table 2 and Table 3, we conclude that the device has the same precision over time, without drifting at any angle after a long period. Next, the device was put in a zero position Fig.21a and moved 90 degrees in roll Fig.21b, 90 degrees in pitch Fig.21c, 90 degrees in yaw Fig.21d, and returned to point zero Fig.21e. After repeating this procedure five times, the device stayed still for 10 seconds, measuring the difference from the initial position, as shown in Table 4:

Figure 21 – Rotations



(a) Initial position (b) Roll rotation (c) Pitch Rotation



(d) Yaw Rotation (e) Return to Initial Position

Source: Elaborated by the author.

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,

Table 4 – Device's precision in repetitive tasks

Results	Differences
Roll	0.186°
Pitch	-1.272°
Yaw	0.088°

Source: Research data.

the pitch angle (rotation in Y-axis) is not used and relevant in the experiment since it stands for the arm's supination and pronation.

5.2 Evaluation from Health Volunteers

Volunteers evaluated the device based on 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.

5.2.1 Delay

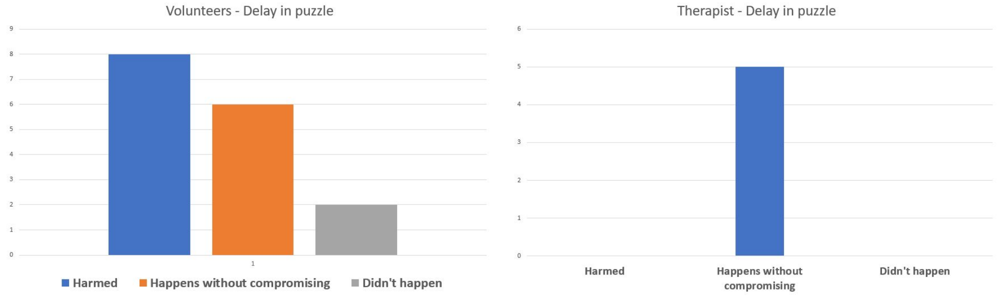
The device's delay is the difference in time between moving the device and its respective arm motion simulation within the VR environment. In this experiment, the volunteers sum a total of 16 healthy subjects and five therapists. They answered some questions about how the delay affected their puzzle experience after using the device.

From these 16 healthy subjects, the delay harmed the puzzle pieces' movements for eight of them; the delay happens without compromising the actions in the opinion of six volunteers, and two subjects did not observe the device's delay. On the other hand, all five therapists answered that such delay is not noticeable for a patient with post-stroke movement disability besides the apparent for a healthy person. Based on these reports, we realized that post-stroke patients' tests would better explain the delay impact.

5.2.2 Motion sickness

Motion sickness occurs when there is a conflict between what the body is feeling and its eyes. For instance, the body is moving, but the eyes sees a still image, which can produce a motion sickness in a person (JOHNSON, 2005; REASON; BRAND, 1975). In virtual reality devices, motion sickness can happen when there is a 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 was resulting in a false screen image (JR, 2000).

Figure 22 – Delay evaluation



(a) Volunteer Evaluation (b) Therapist Evaluation

Source: Elaborated by the author.

The 16 healthy volunteers helped us 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 volunteers agree that there was no such sensation.

5.2.3 Level of Sensitivity

In this experiment, we submitted the 16 volunteers to a sensitivity variation, which means eight volunteers tested the 3x3 puzzle with minimal sensitivity (broad arm movement). In comparison, the other eight volunteers tested the same 3x3 puzzle but with maximum sensitivity (restricted arm movement). Table 5 has the average time to complete the task under such sensitivity conditions.

Table 5 – Average time to complete the puzzle

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

Source: Research data.

The average time got higher in minimum sensitivity because of the broader range of motion needed to reach the pieces. On the other hand, the high standard deviation shows a discrepancy in the time between the users. One of the possible reasons is the initial adaptation of some users when using the device. Some volunteers needed more minutes to get used to the device and the virtual reality environment under the minimum sensitivity setting.

5.2.4 Overall Evaluation

The 16 subjects answered a questionnaire with a few questions about the software. Each volunteer solves the jigsaw puzzle once from the 3x3 puzzle setup. Table 6 shows the question and answers, respectively.

Table 6 – Volunteers evaluation of the Virtual reality puzzle

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

Source: Research data.

The results show that the game can be considered secure, intuitive, and immersive for a healthy person. On the other hand, the game was not considered a fun game for most of the subjects. This impression can mean that the game is too easy or monotonous for a healthy person in a certain way.

5.3 Evaluation from Patients

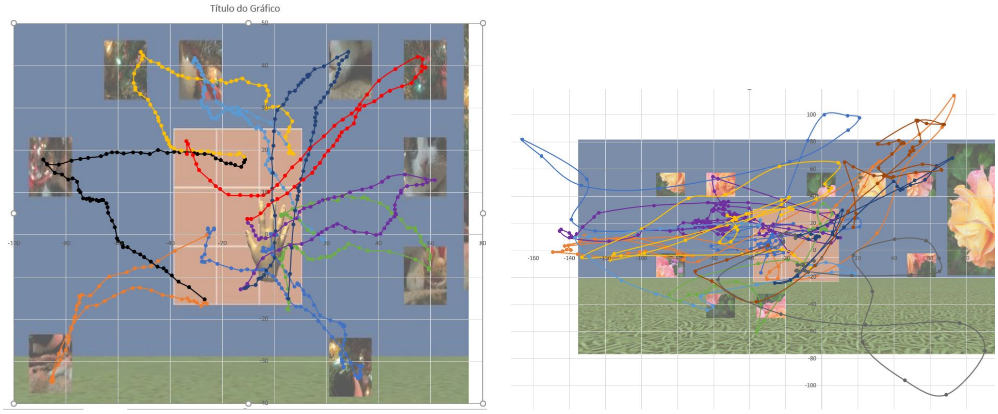
As mentioned before, the device saves all the patient's data in a database for future use. We can plot the data into XY axes as shown by Figure 23a, where it is caught everything made by one volunteer in the VR environment. In this case, the user has no difficulty during the gameplay executing precise movements. On the other hand, Figure 23b has the gameplay of patient "BR." It is possible to see the difference between the patient's movements against those executed by the volunteer in Figure 23a.

However, our system aims to provide relevant data that allows the therapist to follow the patient's evolution through the treatment. Moreover, we propose some metrics next to measure the patient's difficulty, using the device to be immersive within the VR environment. We also report some findings by isolating part of the movement. The system data provide detached data for each part of the movement, as shown by the different colors in Figure 23a and 23b. Figures 24a and 24b shows one movement isolated from the other for better visualization. This isolated movement will be evaluated in the next section.

5.3.1 Overall Performance from Gameplay

We measure few metrics aiming to evaluate how the user performed in the game, such as total time to finish the puzzle, average time for putting each piece in place, and the respective standard deviations. For comparison purposes, the number of pieces, sensitivity, hitbox, and time of puzzle are in the tables below.

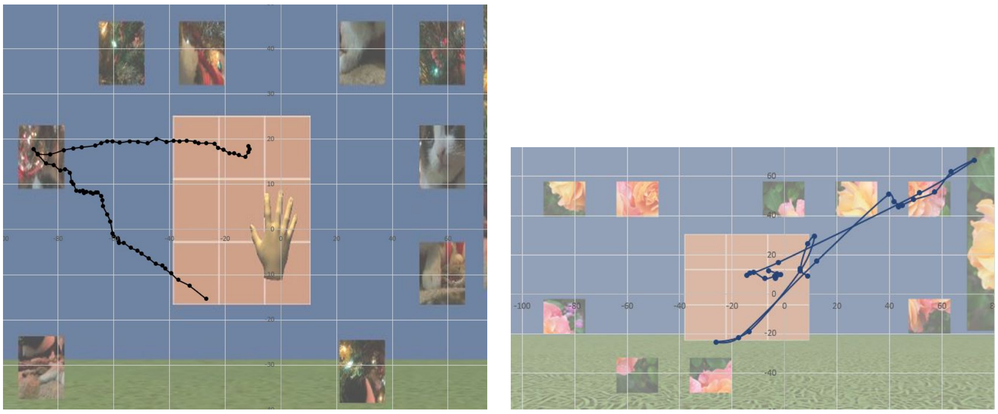
Figure 23 – Puzzles



(a) Volunteer Puzzle (b) Patient Puzzle

Source: Elaborated by the author.

Figure 24 – Movement



(a) Volunteer Movement (b) Patient Movement

Source: Elaborated by the author.

In Table 7, patient BR completes twice the puzzle: the 3x3 jigsaw puzzle and the 4x4 puzzle in another gameplay. The total time almost does not change from 100.89 to 105.18 second, respectively. The patient seems to learn fast how the games work since he/she completed the 9 and 16 pieces puzzles in practically the same amount of time. Another relevant information is the average time per piece, where the patient got 11.21 and 6.57 seconds in both gameplay, respectively, while the volunteer takes 20.95 seconds per piece in one run.

The results can be misunderstood in the first moment once the patient got a better time than the volunteer. BR takes less time to solve the puzzles, but the low sensitivity (1400) and high hitbox (50,60) values make the puzzle faster to assemble. The previous settings allow the patient to complete the puzzles executing with shorter movements. On the other hand, BR's standard deviations are higher than the volunteer's, indicating a more unstable performance to place each puzzle piece.

Table 7 – Evaluation: BR's gameplay

	Gameplay	BR-1	BR-2	Volunteer
Metrics	Total time	100.89	105.18	188.51
	Time per piece	11.21	6.57	20.95
	Standard deviation	7.36	3.19	1.47
Settings	Number of pieces	9	16	9
	Sensitivity	1400	1400	2000
	Hitbox	50	60	31
	Type	VR	VR	VR

Source: Research data.

The patient RB plays the game with two different settings as shown in Table 8. First, he/she solved the 3x3 puzzle three times in sequence, using the same settings for sensitivity and hitbox. In the second set, the therapist decided to change the sensitivity and hitbox values to become more challenging, and the patient played it only once.

Table 8 – Evaluation: RB's puzzles

	Gameplay	RB-0_1	RB-0_2	RB-0_3	RB-1	Volunteer
Metrics	Total time	72.31	74.7	43.21	83.52	188.51
	Time per piece	8.03	8.3	4.80	9.28	20.95
	Standard deviation	7.71	3.54	2.27	3.82	1.47
Settings	Number of pieces	9	9	9	9	9
	Sensitivity	1400	1400	1400	1531	2000
	Hitbox	80	80	80	33	31
	Type	VR	VR	VR	VR	VR

Source: Research data.

The values reached by patient BR follow the similar behavior of those from patient RB. The total time and average time per piece reduce from the first to the third gameplay under the same settings. When the sensitivity and hitbox values change, patient BR also spends more time solving the puzzle. The average deviation of patient BR shows that he/she has the same difficulty moving each piece compared against the volunteer.

Comparing the patient ES with the other patients we noticed Patient ES played the game twice in the same setting, but the therapist chose to increase the sensitivity parameter when compared against the other patients. The metric values indicate that ES had more problems controlling the device to complete the puzzle. We do not know if the difficulty is related to the patient's specific motion disability. However, the high value adjusted for the sensitivity parameter can also explain it or become harder for the patient.

The high level of sensitivity is a reasonable explanation for the volunteer's total time to solve the puzzle. Now, the similar value of sensitivity for ES seems to have a tremendous impact on her/his total time and average time metrics. The patient also had a high standard deviation in time to place each puzzle's piece. It can also be explained by the sensitivity and hitbox values combination and the patient motion problem. Thus, we can conclude that the patient seems to have a severe movement disability or he/she has a problem with the therapist's gameplay settings.

Table 9 – Evaluation: ES's puzzles

	Gameplay	ES-0_1	ES-0_2	Volunteer
Metrics	Total time	563.63	515.72	188.51
	Time per piece	62.63	57.30	20.95
	Standard deviation	43.43	45.41	1.47
Settings	Number of pieces	9	9	9
	Sensitivity	1778	1778	2000
	Hitbox	67	67	31
	Type	VR	VR	VR

Source: Research data.

The last patient, named FA, solved the 2x2 puzzle three times with the same settings. The results are in Table 10, and FA is the only patient that played using FullScreen instead of VR. She/he improved the total time and average time per piece when comparing the first and last gameplay. The performance did not improve in the second gameplay, but we do not know the reason. We have here a high standard deviation in time for FA when placing each piece of the puzzle. The patient learns fast how to play the game, but the time per piece is also slightly higher than RB and BR.

Table 10 – Evaluation: FA's puzzles

	Gameplay	FA-1_1	FA-1_2	FA-1_3	Volunteer
Metrics	Total time	200.87	242.12	74.47	188.51
	Time per piece	50.22	60.53	18.62	20.95
	Standard deviation	40.99	30.88	5.04	1.47
Settings	Number of pieces	4	4	4	9
	Sensitivity	1400	1400	1400	2000
	Hitbox	50	50	50	31
	Type	FullScreen	FullScreen	FullScreen	VR

Source: Research data.

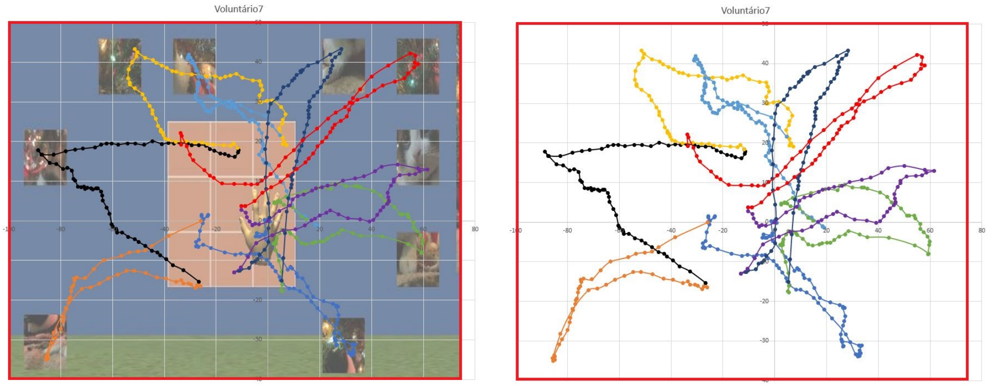
To sum up, we can conclude that the metrics of total time and average time per piece tell us about the patient's adaptability (or learning curve) to play the game from one gameplay to another. The standard deviation progression seems indicate the level of difficulty when placing each piece of the puzzle. As those reached by the volunteers, a low deviation can be a relevant measure of patient improvement. Finally, after a long period of interactions, these metrics' analysis can provide more reliable data supporting the therapists during the treatment.

5.3.2 Control within the Environment

Another relevant analysis is the level of control that the patient has when interacting within the virtual environment. We propose to measure the skill of the player when controlling the hand in virtual reality. One action area (red rectangle) is defined, and how many points the user stays outside that rectangle is measured next. If the user controls the hand only inside the action area, the patient has satisfactory control within the environment.

Figure 25a illustrates how the red rectangle is placed based on the puzzle's position. The action zone placement is larger than the puzzle piece, which means that the puzzle's user never needs to go outside the box. In Figure 25b, the background's remotion gives a clear vision of the volunteer path inside the red box. We will assign a "zero" in the category "environment control" when all the points are inside the action area.

Figure 25 – Volunteer - Control



(a) Environment control with background

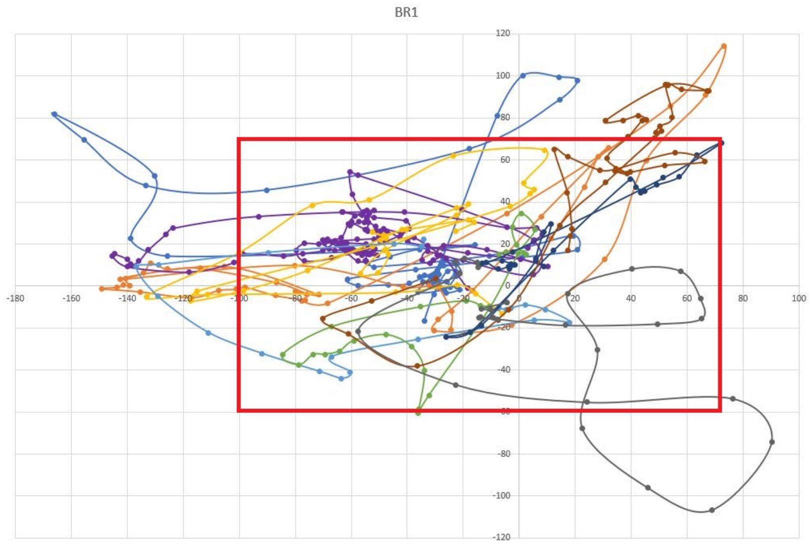
(b) Volunteer7's Control

Source: Elaborated by the author.

The rectangle includes every point from -100 to 70 in its X coordinate and from -50 to 70 in its Y coordinate. The number of points outside the box divided by the sum of all is the proposed metric with results reported in Table 11. Figure 26 shows the control of the environment from patient BR during her/his first gameplay. As expected, the patient has the worst control when compared against to a healthy volunteer. There are 18.11% points outside the action area where the patient tries to keep control, but in a few situations, the movement got out of the box. We must remember that BR is using 1400 of sensitivity (see Table 7) and, if the therapist makes this setting higher, the patient will have even more difficulty solving the puzzle.

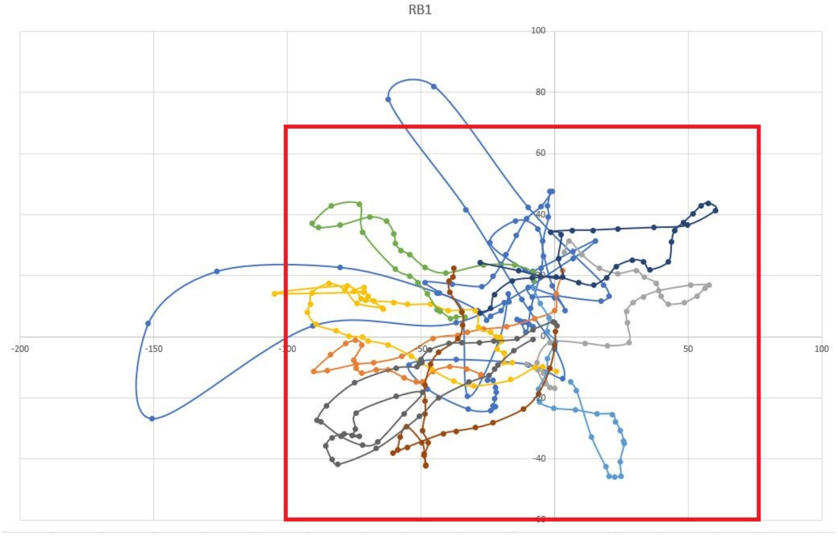
RB is the patient with the highest accuracy in the environment control, as shown in the Table 11 and Figure 27. He/she got only 6 points outside the action area during the first gameplay, and the patient returns to the box fast when it happened. The therapist set the sensitivity parameter to 1531 for RB, which could change up to 2000 to test the movement precision. However, if the main goal is to have the highest range of motion, the sensitivity could go down to 1400.

Figure 26 – BR1 - Control



Source: Elaborated by the author.

Figure 27 – RB1 - Control

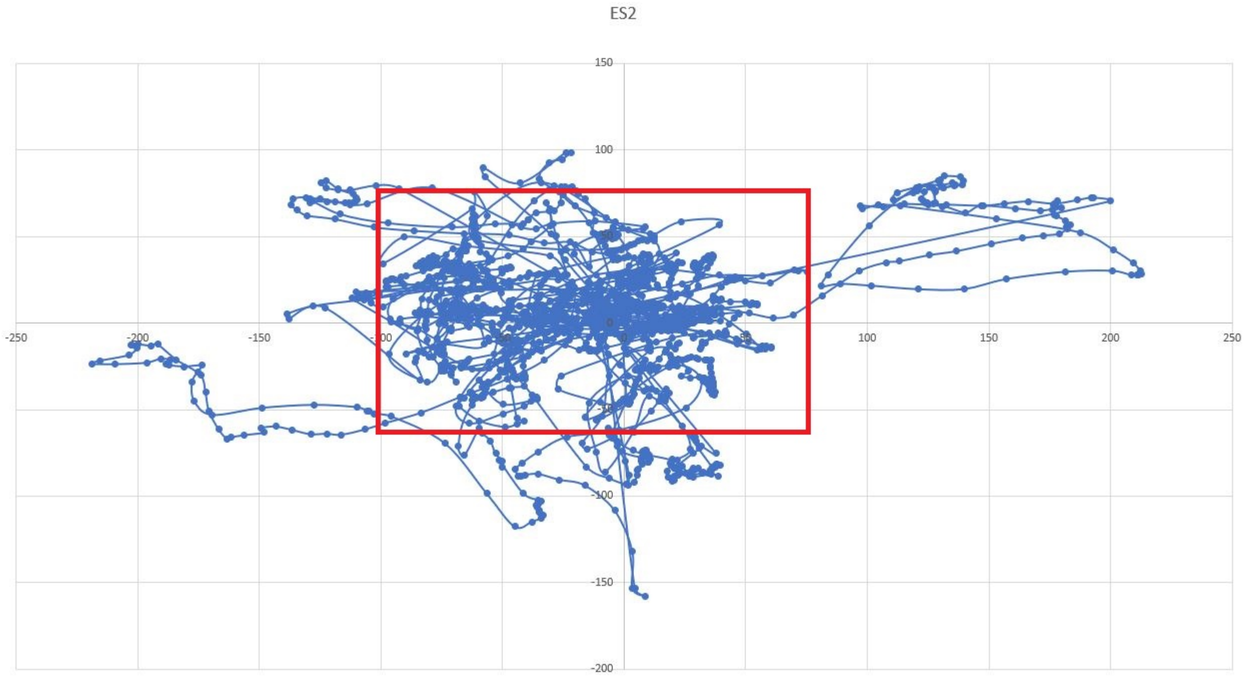


Source: Elaborated by the author.

ES mounted a 3x3 puzzle with 1778 of sensitivity in 515.72 seconds, as shown in Table 9, assuming the second gameplay. The total time and time per piece indicate the patient's difficulty controlling the puzzle inside the box with more precise movements. In the proposed measure for the environment, ES has a higher rate of 18.32% among those using the VR device in Figure 28. If the therapist wants to make the patient uses more precise movements, she/he can lower the hitbox making the game last lesser and maybe more enjoyable.

FA presents the highest percentage of points outside the box among all patients. The patient solved a 2x2 puzzle with 1400 sensitivity (see Table 10), using a full screen and reaching a time per piece of 60.52 sec during the second gameplay. Figure 29 shows the difficulty when

Figure 28 – ES0_2 - Control



Source: Elaborated by the author.

solving the puzzle even inside the box. Thus, FA performance can be related to her/his specific motion disability and/or problems interacting with the full-screen type.

Table 11 – Evaluation: Environment Control

Environment Control	BR1	RB1	FA1_2	ES0_2	Volunteer
Outside Square (%)	18.11	1.73	31.19	18.32	0

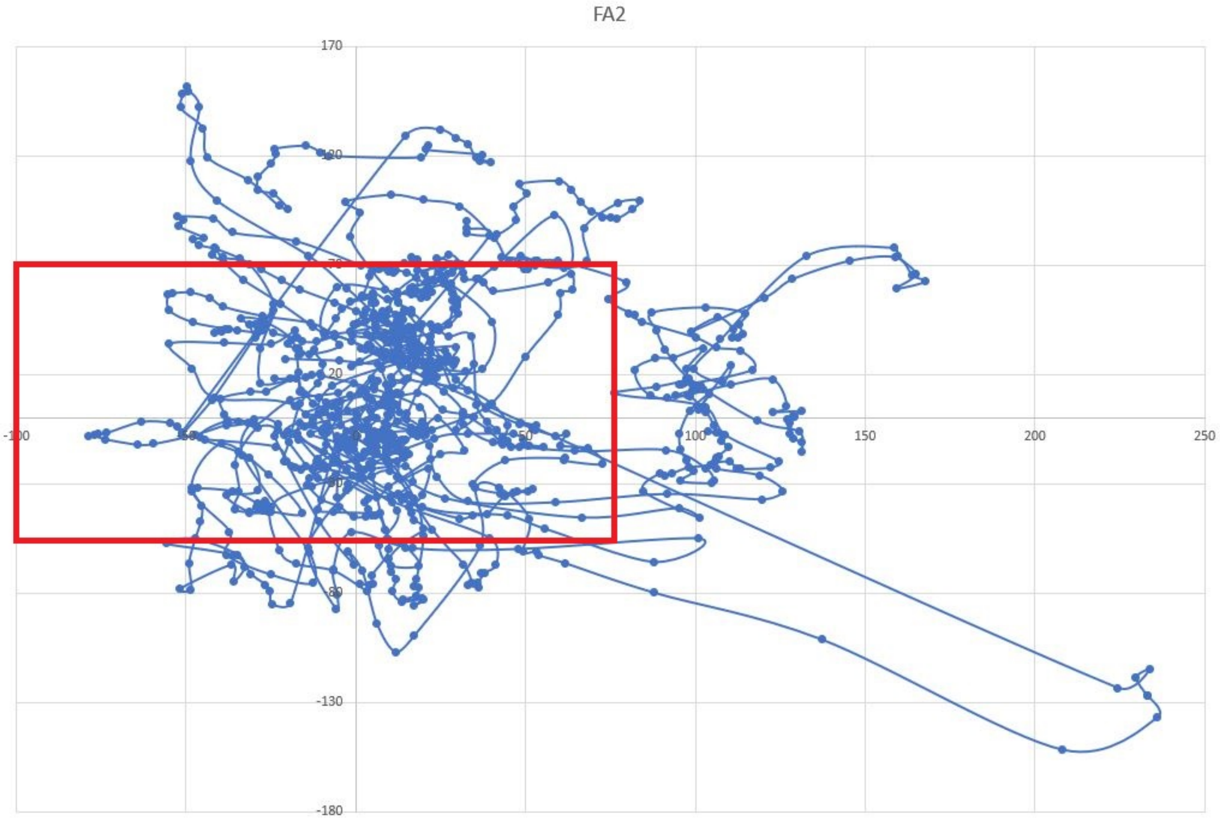
Source: Research data.

5.3.3 Ideal Paths

The last analysis proposed is named "Ideal Path," where we assume ideal a movement executed in two steps. The first step is a straight line from the square's center, with the last puzzle's piece solved, to the square's center for the next piece chosen to be solved by the player. The second step is a straight line from the previous chosen piece to the square's center, where the player must place the puzzle piece. Figure 30 shows the ideal path and the path executed by the healthy volunteer, with and without background.

The patient put the piece in the left bottom square and desire to catch the next piece in the left, defining the first line of the so-called ideal path. Next, the player has to put the piece on the middle top of the puzzle, determining the ideal path's second line. Both straight lines are shown in red arrows.

Figure 29 – FA1_2 - Control



Source: Elaborated by the author.

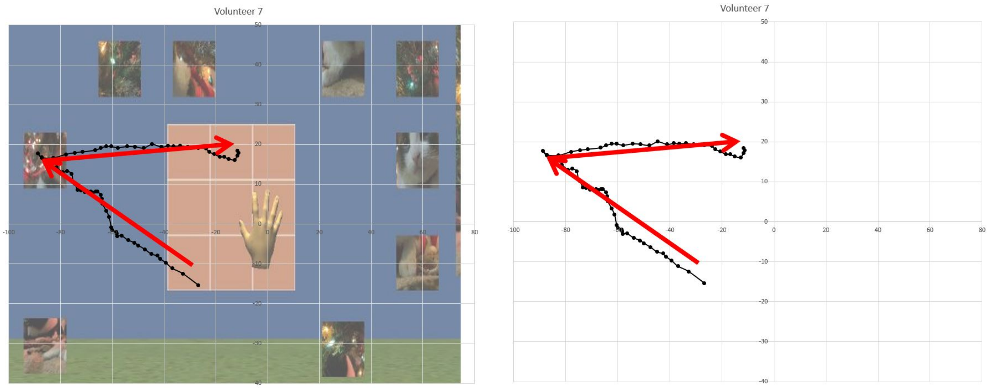
We compare the patient's path against the ideal path by measuring each point's distance to the straight line (Variable "d" in equation 5.1). This is done by calculating the orthogonal projection of each patient's movement over the straight line. However, based on the hitbox setting, the patient does not need to reach the piece's center to catch it. Thus, we subtract the hitbox influence (Δ) during the calculation, as shown by equation 5.1. "X_0" and "Y_0" is the point that we are evaluating and "a","b", ans "c" is from the line equation.

$$d = \frac{|aX_0 + bY_0 + c|}{\sqrt{a^2 + b^2}} - \Delta \tag{5.1}$$

The volunteer (Figure 30) has a satisfactory movement compared to the ideal path. The average distance from the ideal path is 0.21 with 0.49 of standard deviation (table 12). On the other hand, Figure 31 shows that patient BR movement goes far from the "ideal path." The BR's average distance is 11.46 units with 13.04 of standard deviation (table 12). Considering this information and the data from table 11, we conclude that the patient had a problem controlling the game.

The patient RB (Fig. 32) reached the highest score previously without gets out of the red box. RB also achieved the highest score in the "Ideal path" parameter (table 12) comparing to other patients, even considering that her/his hitbox was only 33%. This means that the game

Figure 30 – Volunteer - Path

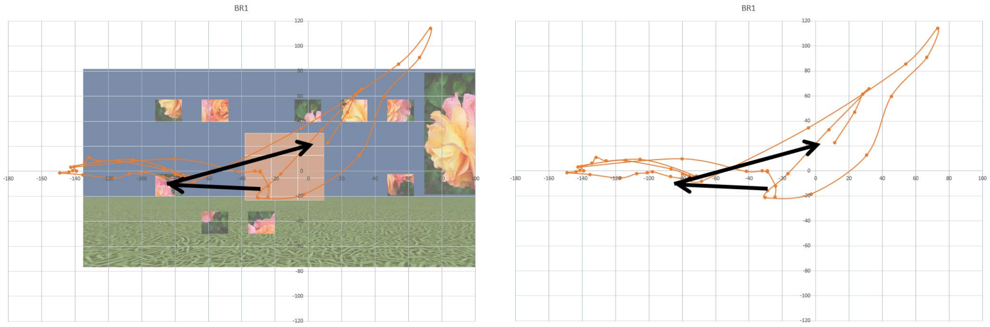


(a) Path with background

(b) Volunteer’s Patch

Source: Elaborated by the author.

Figure 31 – BR1 - Path



(a) Path with background

(b) BR1’s Patch

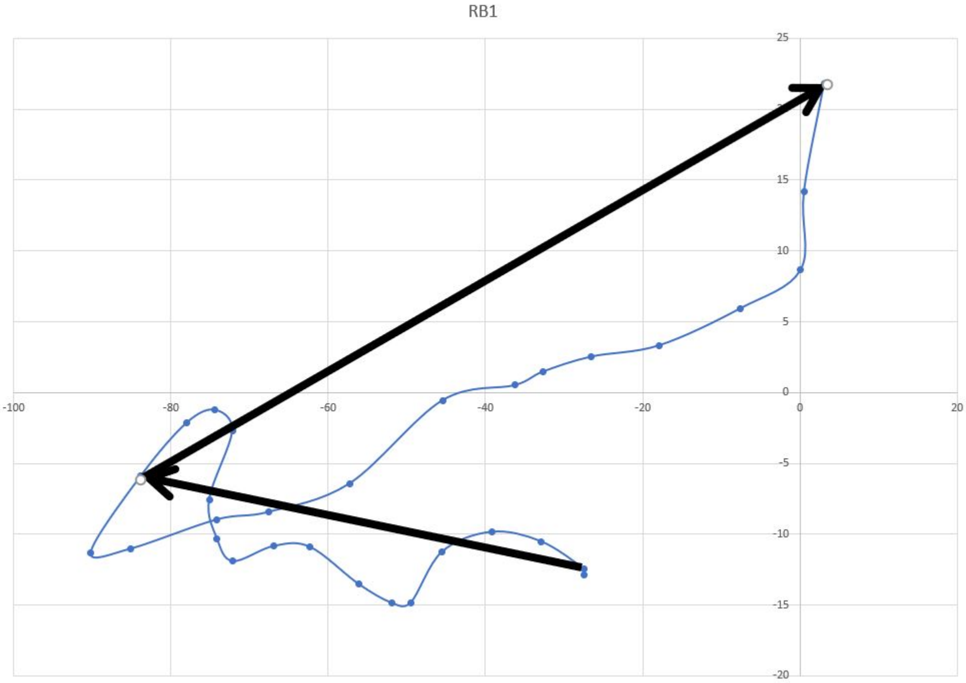
Source: Elaborated by the author.

with that setting was easy for the patient; the therapist could make the game harder by reducing such parameter.

The patient FA had difficulty controlling the puzzle and the environment, returning the average distance of 15. 70 units (table 12) with the path shown in Figure 33). The performance indicates that the therapist should reduce the difficulty level, making the hitbox bigger or changing the sensitivity, based on the therapist’s main goal. All these changes need to be evaluated by the therapist to optimize the rehabilitation process.

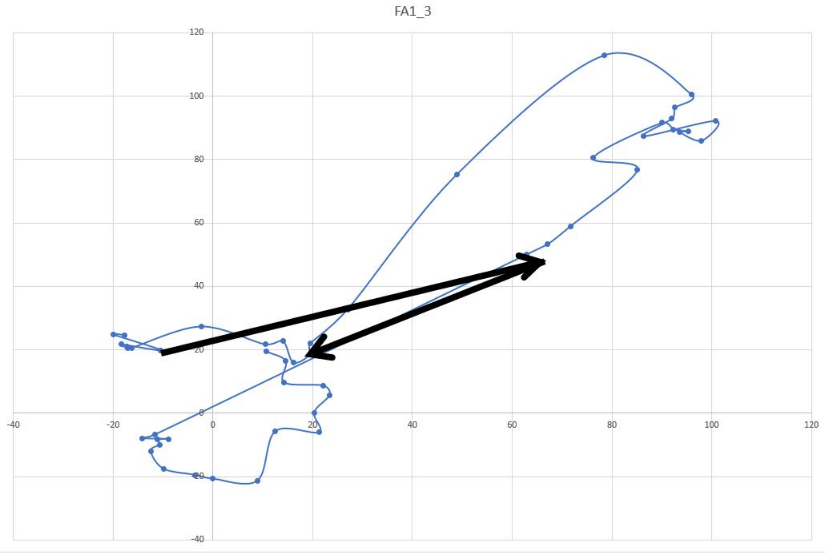
ES shows a satisfactory average distance (table 12) compared to other patients, but this number needs to be evaluated considering the hitbox parameter. In the ES0_1 settings (table 9), we noticed that the hitbox is 67, the highest of all. Therefore, the range of acceptance is much higher than the other patients. The therapist could make the game a little more challenging by reducing the hitbox percentage.

Figure 32 – RB1 - Path



Source: Elaborated by the author.

Figure 33 – FA1 - Path

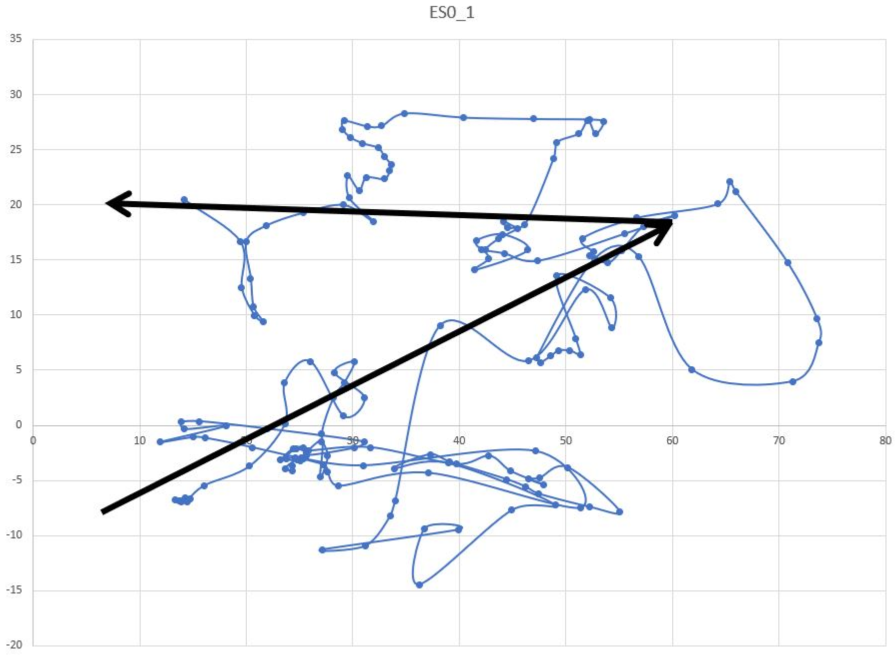


Source: Elaborated by the author.

5.4 Evaluation from Therapist

Four therapists tested the developed system with patients and answered a questionnaire about the proposed device. The questionnaire approaches three main aspects: the patient's interaction with the system, the viability of the whole system in rehabilitation, and the therapist's interaction with the systems.

Figure 34 – ES0 - Path



Source: Elaborated by the author.

Table 12 – Evaluation: Ideal Path

Ideal Path	Hitbox (%)	Average (unit.)	Standard deviation (unit.)
BR1	50	11.46	13.04
RB1	33	1.90	2.55
FA1_3	50	15.70	13.34
ES0_1	67	1.91	3.11
Volunteer	31	0.21	0.49

Source: Research data.

5.4.1 Patient's Interaction

Several issues make the controlling process more complex, such as wrong settings, severe motion's disabilities, cognitive problems, or even lousy software development. In table 15, two therapists considered the game difficult for the user, while the other two have the opposite opinion. The tied results can sustain our previous claim that patients could have problems solving the puzzle based on the therapist's settings (hitbox and sensitivity values).

The second question is related to how the patient understands and interacts with the virtual environment. There are some cases where a healthy user cannot identify virtual objects in virtual reality, and we expected more issues with post-stroke patients. However, two therapists completely discard the misunderstanding of the environment, one of them disagrees with it, and just one considered the current environment an issue.

The third question related to how the patients interact with the system is about motion

Table 13 – Therapists evaluation of the VR puzzle - Patients

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
The patient had difficulty controlling the game.	0	2	0	2	0
The patient had difficulty understanding the game.	0	1	0	1	2
The patient presented some discomfort using the puzzle.	0	0	1	0	3
The patient liked the game.	3	1	0	0	0

Source: Research data.

sickness. As well as the evaluation with volunteers, the patients could have some discomfort using VR. However, almost all therapists reported that there wasn't any discomfort at all. The only case that answers "Neutral" is the same patient that didn't understand the virtual environment.

The last question about the patient is whether the user liked or not to play the game. All therapists agree that the patients enjoy playing the game, which indicates our proposal is a promising approach for rehabilitation. Even the patient that didn't understand very well the virtual world reported that he/she liked the game. It means that the game presents a challenge for the user and a way to enjoy the rehabilitation process.

5.4.2 System's Viability

The following two questions were related to the viability of using the system for rehabilitation purposes. One way to optimize the rehabilitation process is to improve the motivation of the patient. The first question asks therapists about motivation, and all of them considered that the system improves the patient's stimulus somehow. The project's target point is to help the rehabilitation process; therefore, the second question is straight on this matter. All therapists agree about the system as a tool that can help in the rehabilitation process, which is another fair indication of the research's results.

Table 14 – Therapists evaluation of the VR puzzle - Viability

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
This game-based approach motivates the patient.	1	3	0	0	0
The game-based approach assists in patient's rehabilitation	2	2	0	0	0

Source: Research data.

5.4.3 Therapist's Interaction

The last two questions evaluate how easy the therapist settings the system. The parameters adjustment is an appropriate step to turn the game unique to the patient, and it could make the therapist's work more complex. However, three therapists disagree with the first question in table 15, evaluating the system as not hard to set up. Finally, the last question emphasizes the system's effectiveness: "I would use the system developed with other patients in the future". It is imperative to know how the therapist accepted this research's results and whether the project's continuation is something viable. All the therapists answered that they would use the system in future patients.

Table 15 – Therapists evaluation of the VR puzzle

	Strongly agree	Agree	Neutral	Disagree	Strongly Disagree
There was difficulty in setting up the virtual environment for the patient.	0	0	1	3	0
I would use the system developed with other patients in the future	3	1	0	0	0

Source: Research data.

5.4.4 Discussion

We reviewed literature about complementary therapies for motor rehabilitation, such as robotic arms, visual games, immersive virtual reality with several sensors. Based on the review, we concluded that the proposed inertial sensor combined with an immersive virtual reality could be a practical and affordable option to help post-stroke patients' rehabilitation process. Table 16 compares our proposal with the related works in the literature.

Table 16 – Our proposal and related works comparison

Research	**Type**	**Evaluation with Patients**	**Low-cost**
(PIRON *et al.*, 2009)	Vision - VRRS	36	-
(CAMEIRÃO *et al.*, 2010)	Vision - RGS	9	Y
(TUROLLA *et al.*, 2013)	Vision - VRRS	-	-
(SOARES *et al.*, 2014)	Vision - D2R2	36	Y
(KIPER *et al.*, 2018)	Vision - VRRS	136	-
(LUCA *et al.*, 2018)	Vision - BTsNirvana	12	-
(DIAS *et al.*, 2018)	Sonar / Inertial sensor	-	Y
(APPEL *et al.*, 2018)	Camera/Inertial sensor	4	-
This Research	**Inertial sensor**	**5**	**Y**

We introduced a promising inertial sensor within a low-cost system and validated it from clinical tests with five patients. The hardware with an inertial sensor tracks the movement of the patient arm. This approach leaves the therapist free to help the user during the session without compromising the tracking system. The immersive virtual reality employs gameplay aiming to motivate and optimize the recovery process. Based on the therapist's opinions, the whole software system has tailor-made parameters to adjust the gameplay for each patient's needs. In this context, the jigsaw puzzle was developed since it challenges the patient to reach the piece in a 3D movement.

After discussions with therapists, we also developed a second game that focuses on evaluations related to a patient's peripheral vision. The patient focus on the center of the screen and, using peripheral vision, she/he must touch a LED that is ON. There is a quadrant setting where the therapist can evaluate a specific vision area for better treatment. However, we did not validate the second game with patients and therapists. The game description is in the annex of this dissertation as an additional result.

The volunteers' evaluation gave the necessary results for the next phase: patient tests. Unfortunately, in the first month after starting the patient's test, the COVID-19 pandemic got worse. Campinas, Ribeirão Preto, São José dos Campos and São Carlos start lockdowns. The research strongly depends on patients' tests, but our medical partners had to suspend many medical procedures for an extended period. The clinics and therapists that will help in the patient's evaluation had to stop working.

Even with the unfavorable scenario, our research partners provided the data gathered from patients under such conditions. These data are less than we would like to have but enough to report the dissertation's main findings. We identify the influence of the sensitivity and the hitbox parameters over some patients, with some metrics proposed to measure the patient interaction within the environment.

Another critical aspect of the research is the therapist's evaluation of the system. The problem of getting data from patients extends to therapists under Covid-19 situation. However, four therapists helped us with feedback about the system. In their opinion, the proposed VR environment and wearable device provide an enjoyable experience for patients and effectively help or support the treatment.

CHAPTER 6

CONCLUSION

The present Master of Science project developed and evaluated a computational system to support rehabilitation treatments, compounded by an affordable wearable hardware device and an immersive VR environment. The first conclusion is that the proposed wearable device has no problem with drift in the long run. The results from the "stay still," "long-run," and "repetitive task" experiments support such a conclusion. The preliminary test with healthy volunteers also indicates that the device works as a controller within the VR environment. The volunteers did not report motion sickness, discomfort, or delay issues, and they have no difficulty learning to play the game handling the device.

One conclusion is that the total time, average time per piece, and standard deviation give us insights into how the patient evolves after each gameplay. The four patients were able to improve their metrics from the first gameplay to the last. The volunteers metric told us about the influence of a different parameter setting for hitbox and sensitivity. In particular, the standard deviation seems to indicate the difficulty of each patient in solving the puzzle. This difficulty became more reliable through the other two proposed metrics: rate of control within the environment and ideal path. These metrics provide more detailed information about the patient's problems to catch and put pieces within some defined region and how far from a straight path their moves are.

Thus, our initial research question, *Can the low-cost and immersive VR-based protocol developed by this project provide a worthwhile experience for patients and valuable data for therapists?*, can be answered from the results reported. The patients had no problem interacting with the device and liked the experience. The data and metrics provide relevant information for therapists.

As future work, the current metrics and analysis must be validated using data from many patients. Also, the study must advance, taking into account a more significant period following the patient's evolution. The discussion of new metrics with therapists is the next step. An analysis module's development will provide real-time metrics in the software system while the patient is executing the movements.

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ANNEX

A

SOFTWARE: VISION EVALUATION

In the development process the precision and usability of the device, as a controller for the 3D environment, was validated. Because of this the second developed software made use the 3D environment and the hardware to evaluate the peripheral vision from a patient. Nowadays to evaluate the vision by a patient we use a large screen with LEDs (Fig.35), the patient need to focus on the center of the screen and with peripheral vision touch the LED that is ON.

Figure 35 – Dynavision

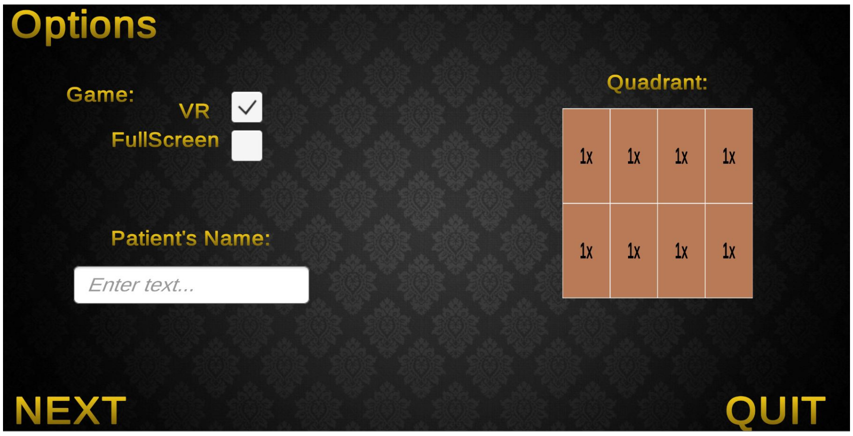
Source: Dynavision ().

One of the application of this software is to evaluate the peripheral vision lost from a after stroke patient. In many cases the patient lost part of the vision, or even completely. Usually the vision lost is irreversibly but with the evaluation of the disability the patient can train the eyes to compensate the issue, minimizing the problems cause by the disability.

A.1 Vision's Settings

The software settings were base on the previous developed puzzle's settings, that's why both of than share a few similarities. The option menu was made to help the therapist in the evaluation process. With this goal there are the following settings: Game type (VR or fullscreen), Patient's name, Quadrants (for precise elevation).

Figure 36 – Software Menu



Options

Game:
VR ☑
FullScreen ☐

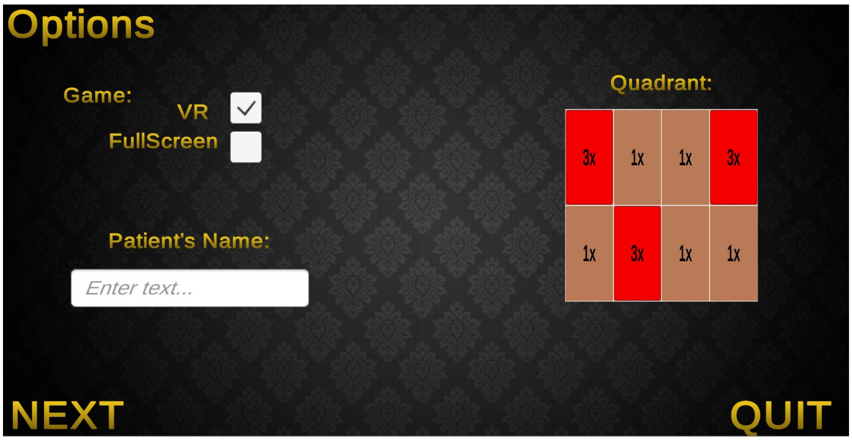
Patient's Name:
Enter text...

Quadrant:

1x	1x	1x	1x
1x	1x	1x	1x

NEXT QUIT

(a) Menu 1x



Options

Game:
VR ☑
FullScreen ☐

Patient's Name:
Enter text...

Quadrant:

3x	1x	1x	3x
1x	3x	1x	1x

NEXT QUIT

(b) Menu 3x

Source: Elaborated by the author.

The patient's name is use to save a file with the software information for later evaluation for the therapist. It's recommended to use the patient's initials for privacy, because this name will be use in a folder/files. In the development process we use a data base system to save the progress of the patients in the section. Unfortunately the vision lost is irreversibly (usually) but if proper training the user cam compensate the disability. The software can evaluate if the patient is compensation the visual disability.

Another important feature of the software is the "quadrant" setting. With this setting the therapist can evaluate a specific area the the vision for better treatment. In Figure 36a there is eight blocks in the "Quadrant" setting, each of these blocks represent the probability of a LED inside the block appears during the game, In other words, if every block is "1X" all blacks presents the same probability to show to the patient. But the therapist can control the quadrant that is more important for him making one (or more) of the 8 blocks three time more relevant in the game's LED selection. Each of the eight block can three time more probability to appears in comparison with a non selected block.

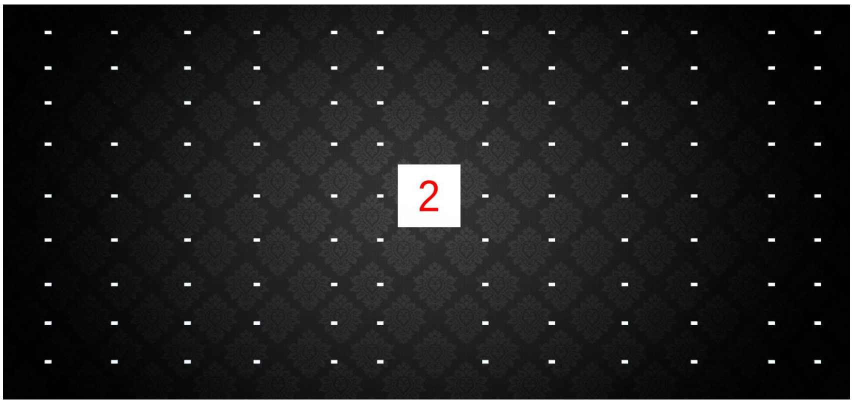
A.2 Vision's Gameplay

The Vision's gameplay consist in a screen (can be in VR or in a monitor) with 108 LEDs spreader evenly across the screen and a number in the middle of the screen (Fig.37). As mentioned before these LEDs are divided in 8 blocks (the Quadrants) each on with their own probability to be selected. First the software randomly select one quadrant, considering all the probabilities. After it the software randomly select one LED inside the selected quadrant, if the patient reach the LED using the hardware developed in the research the software concludes that the patient could see the area that the LED is shown.

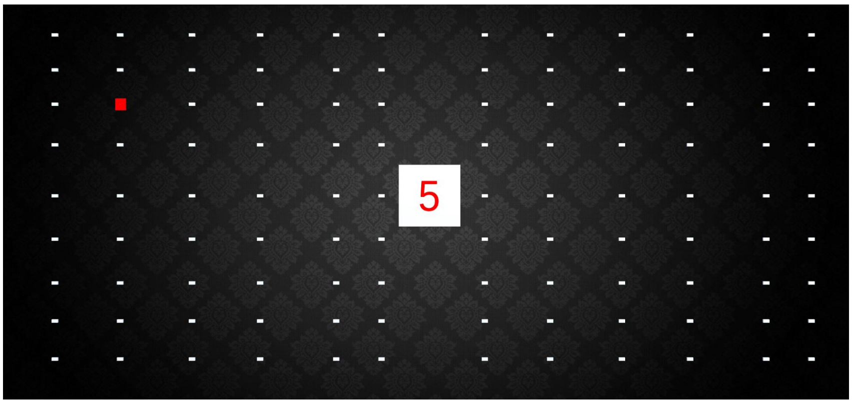
Another important feature of the software is the number in the middle of the screen. This number is a random number between 0 and 9 that changes each few seconds. This feature is important to make sure that the patient is looking in the middle of the screen and not cheating the vision exam.

Nowadays there isn't a correct stop for the exam, the exam ends after 40 LEDs appears. But in future works there will be an AI to better select the LED that will appears inside the block and evaluate the better stop point for the software. In other words, the AI will control which LED will appears based on the patient's feedback during the exam and not just randomly as it is right now. And based on the AI evaluation the software will continue or finish the vision evaluation. In the future this software will presents an previous visual field test (Fig.38, to help the therapist and the patient to understand the disability and compensate it.

Figure 37 – Vision Evaluation



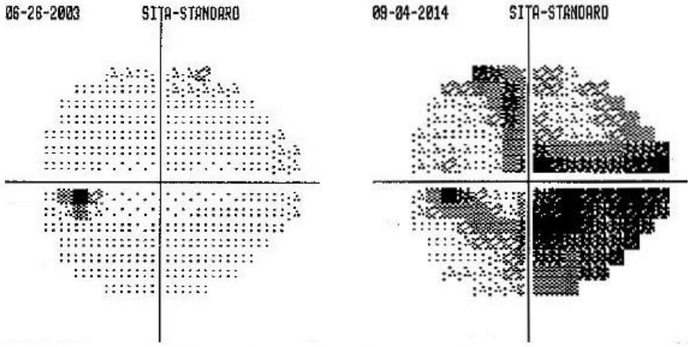
(a) Led OFF



(b) Led ON

Source: Elaborated by the author.

Figure 38 – Visual field test



On the left is a normal visual field. The black spot on the left side is the normal "blind spot."

On the right is an abnormal visual field showing defects that involve both central and peripheral vision; these visual defects are likely to be noticed by the patient.

Source: Visualfieldtest ().

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