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UNIVERSIDADE DE COIMBRA

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Immersive Virtual Reality-Based Serious Games For Therapeutic Rehabilitation

Dissertation submitted to the Department of Electrical and Computer Engineering of the Faculty of Science and Technology of the University of Coimbra in partial fulfillment of the requirements for the Degree of Master of Science

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IMMERSIVE VIRTUAL REALITY-BASED SERIOUS GAMES FOR THERAPEUTIC REHABILITATION

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My area of study has become so complex that I can no longer just google the answer.

Me, Myself & I

Dedication

This dissertation brought me many sleepless nights and several moments of great stress. However, I felt tremendous satisfaction and personal fulfillment in completing it, making me realize how much I like to learn. My personal and professional background is due to my family, girlfriend, close friends and all of my teachers. So I dedicate them all this work. To my friends and colleagues of the AP4ISR team, for making the laboratory a great place to work and for all the coffee times. To my supervisor, Paulo Menezes for all of the guidance and enthusiasm provided during this work and always waiting for more and better. To Ricardo and Bruno, awesome friends I met during the Software Engineering course, for all the fantastic nights working at DEEC, and for providing unforgettable moments. To Gustavo and Carlos, friends with whom I started this journey, for all the moments of great fun, all the dinners, all the support and for being friends for life. To Daniela, my girlfriend who was always present at all times of this stage, for often bringing calm to my stress, for all the support and for all the delicious food that cooked for me during this time. But most importantly, for all the love. The next dinner will be on me. To João, my brother who shared with me most of the time of my childhood, for all the laughter, for all the movies and animes seen and above all for providing suggestions during the development of a website. To my grandparents, because they are fundamental to my life, for all the times they have taken care of me and for all the times they have supported my shopping. Above all, to my parents, Luis and Natália, for all their love and affection, for being the greatest support ever, for making me bulletproof during my education and for always encouraging me to follow my dreams, while keeping me on the right track. To them, I dedicate everything.

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Abstract

The motor rehabilitation process is a crucial step for people who are suffering from the consequences of a stroke, to regain or improve their movements for a better quality of life. However, this process is commonly intense and involves numerous repetitions of advised exercises, which combined with the lack of immediate or short-term visible results leads to problems of motivation and interest on the part of the patient. Thus, patients rarely follow their health-care professionals' advises to perform more exercises at home between physical therapy sessions. Therefore, new solutions to motivate patients should be sought to increase their levels of commitment to their recovery. This dissertation focuses on the development of immersive virtual reality-based serious games for the upper limb rehabilitation, that pursue the same objectives of the conventional motor therapies. By exploring gamification principles and game design theories, it is intended that these therapies become more attractive while providing a playful experience to the individual. To ease the visualization of the results obtained by players, an online back-end application was built that shows the different parameters collected during games, which encode their evolution. A pilot study involving fifteen participants with different impairments was carried out to assess the usability of the proposed system. The results were overall positive, proving that such systems are indeed useful in the aid of the conventional motor rehabilitation therapies.

Resumo

O processo de reabilitação motora é uma etapa fundamental para as pessoas que sofrem das consequências de um acidente vascular cerebral, recuperem ou melhorem os seus movimentos para terem uma melhor qualidade de vida. No entanto, este processo é frequentemente intenso e envolve uma elevada quantidade de repetições de exercícios aconselhados, o que combinado com a falta de resultados visíveis a curto prazo ou imediatos, conduz a problemas de motivação e de interesse por parte do paciente. Assim, os pacientes raramente seguem os conselhos dos seus profissionais de saúde em realizarem mais exercícios em casa, entre sessões de fisioterapia. Deste modo, novas soluções para motivar os pacientes devem ser procuradas de forma a aumentar os seus níveis de compromisso com as suas recuperações. O presente trabalho foca-se no desenvolvimento de jogos sérios imersivos em realidade virtual para o membro superior, que sigam os mesmos objectivos que as terapias motoras convencionais. Ao explorar princípios de gamificação e teorias de design de jogos, pretende-se que estas terapias se tornem mais atractivas, proporcionando uma experiência divertida para o individuo. Para facilitar a visualização dos resultados obtidos pelos jogadores, construiu-se uma aplicação online de backend que mostra os diferentes parâmetros recolhidos durante os jogos, que codificam a evolução dos mesmos. Um estudo piloto envolvendo quinze participantes com diferentes dificuldades, foi levado a cabo de forma a validar a usabilidade do sistema proposto. Os resultados foram globalmente positivos, mostrando que este tipo de sistemas são de facto uma mais valia para as terapias motoras convencionais.

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Introduction

A study on how immersive virtual reality systems may be used as an aid for the conventional rehabilitation therapies of the upper limb is now presented as the leading topic of this M.Sc. dissertation. This section aims to introduce the topic to the reader by presenting its most important aspects and relevance of the study, as well as its main objectives. Some similar works done in the past are presented and discussed, revealing the current state of the art on this topic.

1.1 Relevance of Study

Stroke refers to a *brain attack*, considering it occurs when the blood supply to a certain area of the brain is cut off, leading to oxygen deprivation and the brain cells begin to die. Since the brain controls everything that our body does, such as breathing, memory and muscle control, stroke is considered to be a medical emergency that requires prompt treatment and early actions. Depending on the size of the affected brain area and its location, this traumatic incident causes different types of impairments. However, these impairments usually occur on one side of the subject's body, ranging from weakness (hemiparesis) to full paralysis (hemiplegia) [28].

The recovery process must start as soon as possible as the patient's condition is considered stable. Patients undergo motor rehabilitation therapies that are commonly intense and involve numerous repetitions of advised exercises that have proven to be crucial in order to aid them to recover some of the lost abilities to perform day-to-day activities. As patients spend long periods performing these exercises, without immediate or short-term visible results, their motivation is not stimulated enough to continue performing the recommended exercises at home, resulting in lower and slower recovery rates [36].

Technological devices, such as Nintendo WiiMote, Sony Playstation Move or the Microsoft Kinect, have been introduced in the conventional therapies over time to explore the execution of therapeutic gestures through video games. However, these common console games are not properly adapted to the patients' difficulties, and often require movements that are beyond their capabilities. This direct mapping between their actions and the necessary controls to play, often result in frustration or even quick disapproval of those games.

New solutions to motivate patients must be explored to increase their engagement and commitment levels with their therapies, and this can be achieved by taking purposeful games into their lives. The success and proliferation of Virtual Environments (VE) comprehending Serious Games (SG) have grown into a significant topic of interest [15, 37, 41] and have shown success in many different areas of application, such as education [20, 51], health care [32, 25, 19], cultural training [52, 24], and even military [53, 44]. This new kind of video games use the advances in game design and computer graphics hardware to perfectly blend both pedagogical and entertainment aspects, and are sometimes associated with the concept of edutainment[1]. In fact, the main purpose of serious games is to teach users something or even allow them to (re)learn some desired skills, rather than only entertaining them while playing [37, 17]. Virtual Reality (VR) and Head-Mounted Displays (HMD) are increasingly popular these days, as they allow game designers to transport users into ”new realities” and support experiences through sensory stimulation. When applied to motor rehabilitation, patients that wear an HMD won't be able to see the affected body parts, creating the perfect opportunity to map their possible movements into the required controls and therefore focus on the game itself.

In short, carefully designing Virtual Reality-based Serious Games for Therapeutic Rehabilitation opens up a panoply of new possibilities given the value that they can add to the

[1] Edutainment is a derived word from ”Education” and ”Entertainment”, that characterizes contents that educate while being entertained [9].

well-established therapies.

1.2 Main Objectives

Following the same objectives of the traditional therapeutic approaches and exploring gamification principles, the main objective of this work is to develop VR-based serious games for the upper limb rehabilitation that provide a pleasing experience to patients while avoiding any type of frustration given their handicap. The enjoyment during the training encourages them to perform a higher number of repetitions of beneficial exercises, leading to a better and eventually faster recovery process.

Moreover, the system should be used by different health professionals, allowing them to have multiple patients training at the same time, stimulating patients' autonomy. As a result, it will become a useful tool for the clinical environment, but should also be qualified for home deployment, so that patients can continue their recovery process at home.

To sum things up, the design of the rehabilitation gaming system has the following objectives:

- An extensible platform that allows the integration of one or more serious games with different therapeutic purposes for aid of the conventional therapies.
- Contribute for an overall improvement on the quality of the current motor rehabilitation therapies, by having the patients engaged with the agreed goals.
- Possibly leading therapists to have more than one patient training at the same time, while their performances are being monitored and saved for later evaluation.
- Promote patient's autonomy during training.
- Suitable for home deployment.

1.3 Related Work

In order to understand what is the current state of the art and how technologies may aid motor rehabilitation, a few works that have been done so far are presented and discussed below.

Using GestureTek's GX, IREX platforms and Sony Playstation + Eyetoy, a group of researchers proposed that Video Capture Virtual Reality would be a flexible and effective rehabilitation tool [49]. This method refers to a video camera and software used to track movement in a single plane, without the need of using markers on specific locations. They designed a set of games that uses this technology in order to prove their idea. After evaluating it with patients, they concluded that some of them had balance improvements similar to conventional therapy, but with increased pleasure, as well as improvement on motor dexterity.

A specific framework for Virtual Reality movement therapy was designed in [30]. This framework consists of a number of serious games that were carefully designed and developed in order to encourage patients to perform physical exercises in adaptive virtual environments, focusing on speed, range of motion, dexterity and enhancing endurance. These systems also allow the user performance to be monitored and analyzed over time [38].

Two game design principles that should be considered were identified in [15]: meaningful play and challenge. At the start the game should have low level of challenge and gradually increase as the players become familiar with the game or improve their abilities. A meaningful play emerges from a game in the relationship between a player's actions and the system's outcome. In order to prove their concept, they created and tested different games either using Virtual Reality and Screen-based experiences, which were adaptive to the subject's performance and supported user profiling (saving data for later evaluation). They concluded that games which are properly designed and adapted to patients' needs can be highly engaging and even addictive, while promoting limb movement benefits.

A serious game named *CONTRAST* focuses on arm-hand training for stroke survivors using every day physical objects and adapting game's difficulty according to patient's performance [23]. They asked two stroke survivors to play the game for one hour a day, during one week, in order for them to evaluate it in terms of motivation and engagement. After one week, one participant decreased the erroneous response of his ill hand while sliding an object, and both participants found the game engaging and encouraging. Therefore, they concluded that the game was motivational and might be used for therapy aid.

A low-cost system for upper limb rehabilitation presented in [45] makes use of three modules: a passive manipulator that supports horizontal motion against gravity, Kinect and Leap Motion cameras for motion tracking and an VR game that simulates fish feeding. The player must take food and place it near the fish, as he/she successfully completes this task, his/her score increases.

MoVEROffice is a serious game that makes use of VR and natural interaction for upper limbs rehabilitation [10]. The objective is to have patients acquiring skills in performing given tasks in the virtual environment, for later transfer into their daily activities. They conducted an experiment in order to compare the performance of people with restricted mobility and without. Results of this experiments have shown that the performances were similar, which means that the impairments did not influence it.

Recently in the Department of Electrical and Computer Engineering at the University of Coimbra, a work was elaborated by a colleague in the scope of a master's dissertation that aimed to develop a serious game for the aid of the motor rehabilitation therapies [29]. This serious game aims to motivate and encourage patients to perform therapeutic exercises, through a playful activity that will cause them pleasure during the session.

1.4 Key Contributions

Considering the current state of the art discussed above, the work described in this document focus on development of a serious game that concerns motor, sensory and cognitive stimulation, as well as having a platform that allows the integration of more serious games for different therapeutic purposes.

1.5 Structure of Dissertation

This dissertation is organized as follows:

- **Chapter 1** explains the relevance of this study and its main objectives, comparing it to the current state of the art.
- **Chapter 2** describes the target patient condition and the commonly used therapeutic procedures for motor rehabilitation, and how serious games and gamification principles can be linked to them.
- **Chapter 3** presents the system outline and how to map the users' movements into the required controls, focusing on the developed serious game and on the interface specifically developed for therapists.
- **Chapter 4** shows the results obtained from the pilot study that was conducted and from patients' game play.
- **Chapter 5** discusses the obtained results and the final evaluation by therapists.
- **Chapter 6** concludes the dissertation by drawing conclusions from all the work developed and indicates the follow-up work that is considered to be relevant in the future.

2

Background on Virtual Reality Serious Games for Therapeutic Rehabilitation

2.1 Target Patient Condition and Therapeutic Phase

As noted in chapter 1, one of the most common consequences after having a stroke is partial (hemiparesis) or total (hemiplegia) paralysis on one side of the body, usually corresponding to the contralateral side of the affected area in the brain. This paralysis is marked by a change in the muscle tone of the patients, the continuous or partial contraction that muscles perform when they are at rest, or the resistance of muscles to passive movements (for example, the effect that gravity has on the human body). So, after this traumatic incident, patients have difficulties in performing any kind of movement and struggle to keep their affected limbs in stabilized positions because of *hypotonia*. *Hypotonia* is defined as a decrease in resistance to passive movement. Over time, it is common to have it replaced by *spastic hypertonia*, which is an abnormally increase in patients' muscle tone, muscles become very rigid complicating movement execution and leading to abnormal postures and stereotyped moves [42].

To regain normal muscle functioning, patients undergo complex motor rehabilitation therapies that begin with exercises to strengthen the muscles of the arms and shoulders, and later for those of the hands and fingers. However, to make patients' recovery as efficient as possible, appropriate objectives should be set in terms of their muscle tone following a scale [40]. A scale presented in [35] can be used define three different degrees for spasticity, rigidity and flaccidity: *Mild* (1), *Moderate* (2) and *Severe* (3). For people who do not have any changes in muscle tone they are assigned *Normal* (0). Changes in muscle tone considered *Moderate* and *Severe* are associated with earlier stages of rehabilitation, where range of motion is reduced and there is greater difficulty in performing movement. And for the scope of this dissertation, it is intended to reach these earlier stages of rehabilitation.

However, depending on the affected region of the brain, other disabilities may occur in speech, swallowing, vision and cognition. The most common type of visual issues is *hemianopia*, which means losing the left or right visual field of both eyes. Having partial visual field loss, means that the patients are unable to see a section of their vision area, resulting in blind zones. Visual scanning training is a technique that encourages patients to look to their left and right sides in a systematic way, reminding them to look on their blind slide. Visual processing problems are related to the brain having difficulty processing the information received by the patients' eyes, resulting in a reduction of object or people recognition capabilities [2, 46].

According to [39] there are six neuropsychological domains that comprehends different types of functions used by the brain to produce certain behaviors. These neuropsychological domains are:

- Attention/Concentration - ability to focus awareness on a specific task or stimulus, to concentrate on it long enough to accomplish something, or even to shift between tasks.
- Language - various types of skills related to languages are covered by this domain.
- Visuospatial Skills - ability to represent, analyze, and mentally manipulate objects.
- Motor skills - abilities such as gross, manual fine-motor, and facial fine-motor are covered by this domain.
- Executive Functions - allow humans to use a variety of higher-order functions, such as planning, conceptualizing, organizing, and so on.
- Memory - everything related to memory and learning is covered by this domain.

Due to the complexity of a stroke, different domains can be affected either separately or simultaneously. In most cases, the domains of motor skills, attention and memory are the most affected [2].

Moreover, responses to external stimuli vary from person to person. Stroke survivors typically have a slower response to them, as the recognition of actions and events is also slower. In the worst case, they may even have lost a large portion of their reaction capabilities, is almost null [2].

2.1.1 Common Therapeutic Procedures for Motor (Re)Learning

The functional outcome from the motor rehabilitation process after stroke is heterogeneous in its nature, since different patients naturally have different difficulties and recover differently over time [21]. Thus, the different therapeutic approaches used in clinical environments are presented below, which aim to encourage exercises that are specifically tailored to each individual patient and to dismantle complex activities into simpler movements [34, 18, 47]:

- Bilateral arm training involves the use of the healthy upper limb to support movement of the affected upper limb (paretic limb) for identical activities in simultaneous.
- Constraint-induced movement therapy (CIMT) induces motor learning by performing many repetitions of task-specific training for the affected upper limb while having the unaffected one immobalized.
- Fitness training, or physical fitness training, uses a structured plan of regular physical exercises to improve or maintain either cardiorespiratory fitness, or strength and muscular endurance.
- Mirror therapy consists on the use of a mirror placed in a certain position that reflects the non-affected limb as it was the affected one. Thus, movements of the non-paretic limb will create the visual illusion of normal movements of the paretic limb.
- Occupational Therapy aids patients to recover activities of daily living, such as dressing or cooking, as well as leisure activities.

- Repetitive Task Training demands many repetitions within a single training session in order to attain a clear functional objective.
- Strength training is based on progressive resistance exercises in order to improve muscle strength.
- Splinting or Orthosis refers to external devices that are used to improve functional movement, while reducing spasticity or pain, or even to prevent other complications such as contractures.

Exercises in figure 2.1 are some of the movements that can be performed by patients both with or without therapist supervision. They allow patients to recover muscle strength of arms and shoulders.

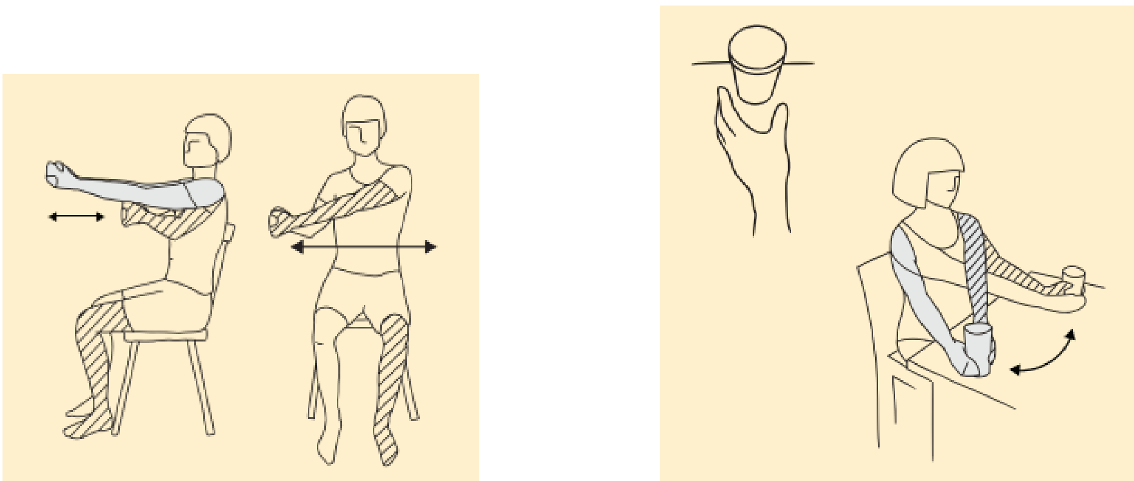


Figure 2.1: Example exercises that can be performed by patients while sitting. Taken from [8].

2.1.2 Sensory Stimulation on Motor Rehabilitation

Motor rehabilitation is strongly associated with performing many repetitions of exercises that promote muscle strengthening. However, after a central nervous injury caused by a traumatic incident, such as stroke, the brain has to adapt its function to a whole new situation using neuroplasticity mechanisms, to maintain control of everything that the human body does, such as motor coordination [31]. Neural reorganization and neural adaption serve as foundation for the brain to remap its sensorimotor interactions either by transferring functions from the damaged areas to the adjacent healthy ones or by establishing new neural pathways, while still reinforcing the remaining neurons. This leads researchers to believe that any type of motor stimulation indeed implies sensory information [16, 14].

Made-up sensory information takes this one step further, as it allows patients to perceive that they are performing a task without actually completing it alone by themselves. Using technologies such as virtual reality or augmented reality, the patients' possible movements of the affected limb can be translated into the movements necessary to perform a task, misleading their perception. Most human learning is based on the observation of someone executing oriented-object actions, triggering our mirror neurons. These visuomotor cells can be linked to the motor (re)learning and allow the brain to better consolidate its sensorimotor representation [11]. In addition, if the handicap comes from from the damage caused to the referred neural pathways of the affected limb, using alternative stimuli such as sound, haptics or visual during a gaming session, will enable patients to (re)learn how to perform and enjoy the demanded exercises, contributing to their recovery process [28].

2.2 Serious Games and Game Design Theory

Game-based learning is currently in vogue since video games have reached audiences never before imagined. When properly and carefully designed, these video games create a sense of engagement, pleasure, and presence that results in a boost to the user's motivation [33]. Although being strongly associated with a pure entertainment experience, they serve a much more noble purpose: to allow the user either to (re)learn a new ability, or even to train some desired skill [37]. These powerful tools are called serious sames and have had a huge impact on our society, as they have many different areas of application, as referred before.

Gamification can be described as a technique of bringing game-related elements to non-game contexts. It can provide playful experiences for repetitive and monotonous tasks, helping users to become more motivated and engaged with non-game scenarios [26, 13]. Some of the most common game elements have been collected and are described in table 2.1. To be able to include them in serious games applied to motor rehabilitation therapies by following these gamification principles, two game design frameworks are discussed below.

Game Element	Description
Objectives / Tasks	Something that players have to achieve or work towards.
Feedback	For every action performed by players there should be immediate notification of their progress or failure.
User Levels	Encodes the player's proficiency throughout the game.
Score	Total points obtained the game-play.
Point System	Number of points that are added to the score for a successful completed action.
Achievements	Players can establish goals for themselves.
Leaderboards	Allow players to compare their performance to others.
Rules	Describe how the game is played.
Time Pressure	Reducing the time that players have to complete a task can serve as way to help them focus on the problem.

Table 2.1: Common game elements and its description.

The Mechanics-Dynamics-Aesthetics framework, or simply MDA framework, is a formal approach under the game design theory and its development that breaks a game into three different elements: rules, system and "fun" [22]. It depicts the relationship between the designers/developers, who create the game by defining the rules of the system, and the players, who will later consume the game to have fun while using it. This framework also establishes the involved design counterparts during this process as *Mechanics*, *Dynamics*, and *Aesthetics*. *Mechanics* represent the back-end of the game, defining every game component that encodes the data representation, algorithms and control mechanisms. Along with the game's content, *Mechanics* generate *Dynamics*, which refers to the run-time behavior of the game for every action of the player over time, creating aesthetic experiences. Therefore, *Aesthetics* describe the desirable emotions evoked in the player, such as the feeling of challenge.

Even though the MDA framework has proven to be a successful approach for designing game-play, it only focuses on the entertainment aspects. The *Design*, *Play* and *Experience* framework was created as an extension of the above to address the needs of learning that exist in serious games [50]. It states that the game is created by a team of designers/developers and played by users, resulting in player's experience. Once the game's objectives are defined and a prototype is ready, it should be tested among the players in order to assess the user experience. The outcomes of this test are analyzed to understand if the desired user experience have been achieved or it is required a new iteration on the game's design, leading to an iterative loop between the *Experience* and *Design* counterparts. The loop shown in figure 2.2 guarantees that the desired learning effects by playing the serious game are fulfilled among players. For instance, as the game-play is strongly influenced by the player's cognitive background, the target audience should be taking into account during the design process.

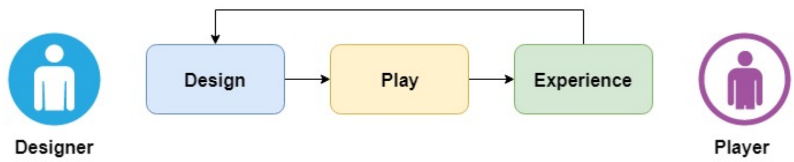


Figure 2.2: Iterative loop between *Experience* and *Design* in the DPE framework.

2.2.1 VR Serious Games for Motor Rehabilitation

The use of virtual reality technology along with the properly designed serious games for rehabilitation has grown into a significant area of interest [15, 37, 41]. Its main purpose is to make the exercises necessary for patient recovery easier and more enjoyable than traditional therapies. Therefore, VR-based rehabilitation has some documented advantages over the conventional therapy are: increased frequency and more repetitions during the exercises, better patient engagement, enhanced motor (re)learning by visual stimuli, the ability to track the patient's recovery progress over time and could require low clinical supervision (easing home use and enabling distance rehabilitation) [47, 27]. But also, playing serious games also stimulates the development of basic learning skills, such as paying attention, promoting visual-motor coordination, improving logical spatial reasoning and orientation, among others [12].

3

Proposed System

3.1 Requirements gathered based on Therapists' Feedback

Like any project that seeks to escape failure, functional and non-functional requirements must be carefully collected and defined. Functional requirements should spell out what the system does, while nonfunctional requirements specifies criteria for its operation. Thus, during some visits to a local rehabilitation center, Caritas Diocesana de Coimbra, it was possible to gather valuable suggestions, which have been converted into requirements, presented in tables 3.1, 3.2 and 3.3.

The development should be performed on top of the *OpenAR*, a graphics and animation engine developed in the Institute of Systems and Robotics. The main reason is that it provides the basic support for manipulation and rendering of 3D objects and scenes, as well as the necessary support for interfacing with Bullet physics simulation engine, *Oculus Rift*, and is completely customizable to suit the needs. As such, if a new class or method is required during the project development, it can be easily integrated within the *OpenAR*. The developed application should be executed on top of a Linux desktop or a laptop computer.

Requirement	Short Description
1	Initialize the system.
2	Play with or without the Head-Mounted Display.
3	Calibrate the Magnetic Sensor by performing a sequence of steps.
4	Customize the different buttons to be used during the game play.
5	Customize the different gestures to be performed during the game-play.

Table 3.1: Non-functional requirements for the user graphical interface.

Requirement	Short Description
1	Manage Patients
1.1	List all the existing patients
1.2	Add a new patient
1.2.1	Insert information about patient's name, age and a following description.
1.3	Remove patient
1.3.1	Confirm action
2	List all the existing serious games
3	Visualize information about patients
4	Manage patient's parameters for each serious game (starting level, starting speed, ...)
5	Visualize patient's progress throughout sessions by observing different provided information on total distance covered, total played time, total number of sessions and graphics for scores, final levels, distances, played times, ...

Table 3.2: Functional requirements for the therapist graphical interface.

Requirement	Short Description
1	Friendly-user interface.
2	Expansible platform that allows the integration of more serious games for different therapeutic purposes.
3	Easy to move around.
4	Uses little space.

Table 3.3: Non-functional requirements for the overall system.

3.2 System Outline

The overall system comprehends a distributed architecture and it is composed of three different elements: the gaming application, the *RehabGames* database and the online back-end application for therapists, as shown in figure 3.1. The gaming application may be deployed in different desktops/laptops. This way one or more patients may initialize the system through a friendly user interface and then play serious games for a desired amount of time. While they are playing, their performances are being monitored and saved in a local file. As they finish their session, the collected data is organized and then uploaded to a remote database (*RehabGames*) via an internet connection. Subsequently, data regarding the use and evolution of patients can be recorded, even at home, while allowing therapists to consult it whenever desired.

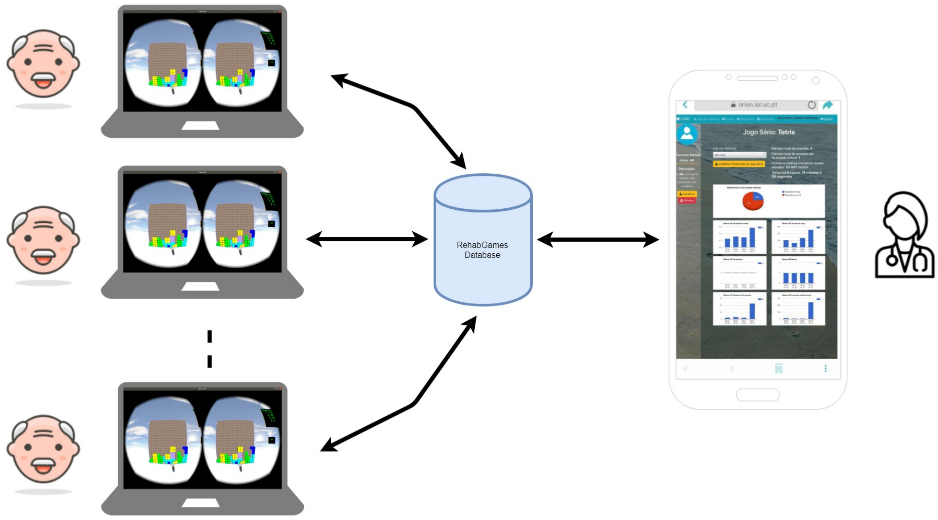


Figure 3.1: System's architecture.

3.3 *RehabGames* Database

The *RehabGames* database is absolutely an integral part of the system described in this document. The entity-relationship diagram presented in figure 3.2 illustrates the logical structure of the database, while displaying five different entities: *therapist*, *patient*, *game*, *parameters* and *session*. These entities have attributes that define its properties, as described below:

- Entity *therapist* stores name, username, email and *hashed* password for each therapist.
- Entity *patient* stores name, pathology and age for each patient.

- Entity *game* stores its name, the parameters that can be altered by a therapist and the options that the patient can choose.
- Entity *parameters* stores the value for the parameters set by a therapist, for each relationship between patient and game.
- Entity *session* stores the collected data regarding the use and evolution of patients for each playing session that they perform.

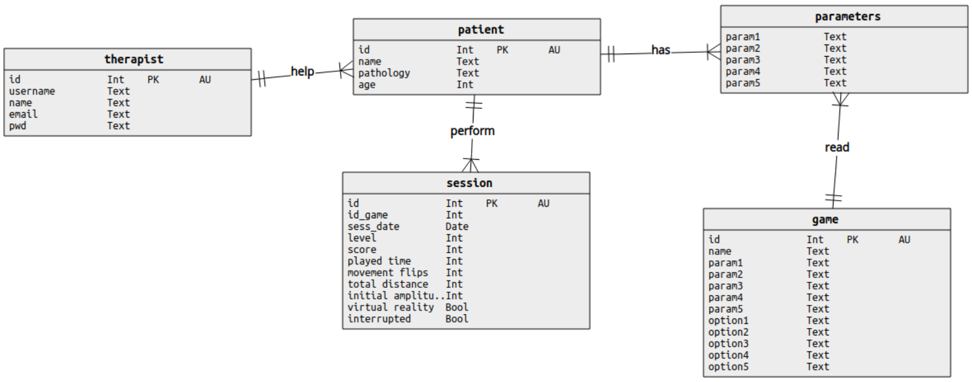


Figure 3.2: Entity-relationship diagram for the *RehabGames* database.

3.4 Tracking Patient Upper Limb Movements for Game Controls

As stated from the above, the main objective is to have the user performing therapeutic exercises for the upper limb, which have to be somehow translated into the game's environment. This process may be referred as the estimation of the user's hand pose and can be performed by several different methods, such as computer vision techniques, magnetic sensors and optic flow sensors. However, the solution considered to be the most suitable for this purpose is the one that involves less computational power, being low cost and easy to move around, such as the Razer Hydra Motion Controllers.

The Razer Hydra is a motion-sensing controller for the personal computer, commonly used for gaming purposes, developed by *Sixense Entertainment* [5]. It is composed by two controllers for each hand of the user and a base station, as shown in figure 3.3.

Figure 3.3: Razer Hydra PC Motion Sensor Controllers.

The base station is responsible for computing the absolute location and orientation of the controllers, down to a millimeter and degree precision, based on the created weak magnetic field. Each controller is composed by five regular buttons on the top side, along with the joystick, and two buttons in other side, as shown in figure 3.4. Although, being a wired device, it allows six degrees of freedom in three-dimensional space, meaning that it will mirror exactly every movement into the game's environment.

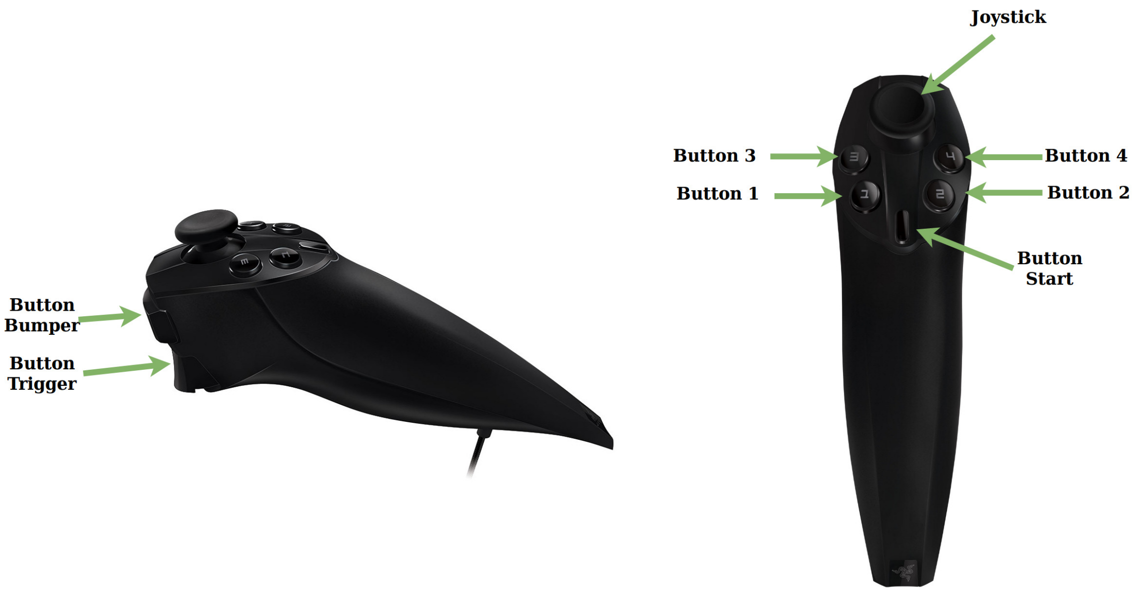


Figure 3.4: Available buttons on each Razer Hydra Controller.

Withal, it is necessary to keep these controllers away from objects that emit their own magnetic field, such as transformers, as they may generate errors when calculating the position and orientation of the controllers relative to the base station. Also, according to [5], this equipment uses a magnetic field so weak, that it may be used without any kind of negative impact to the objects in its surroundings.

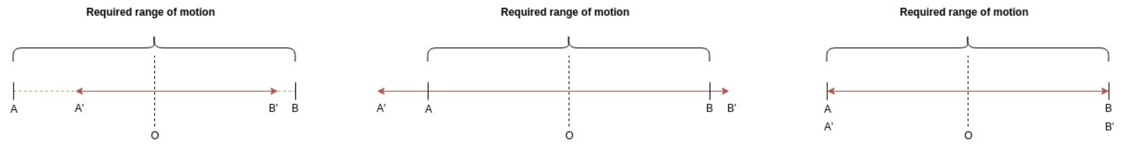
3.4.1 Calibration Process

Different patients have different muscle conditions/impairments, meaning that before the game starts it is necessary to understand what is the range of motion that the user can perform, by completing a calibration. In physiotherapy clinics, there are some machines responsible for helping patients to execute useful therapeutic gestures in their recovery, which before such use require this kind of process. If the machine isn't correctly calibrated, it may lead to injuries. But, when playing a game, if the users are unable to meet the objectives, they will feel frustrated and quickly disapprove it.

Under the supervision of a therapist, a sequence of steps that should be executed by the user has been defined, which are presented below:

1. Press a button to the start the calibration;
2. Perform a movement to the left greatest extent of the playing area and press a button;
3. Perform a movement to the center and press a button;
4. Perform a movement to the right greatest extent of the playing area and press a button;
5. Perform a movement to the center and press a button.

The result of this process may be represented in figure 3.5, showing that the game area is divided into two hemispheres. When the user lacks in the range of motion, the system should be able to augment its movements by calculating an offset for both of the hemispheres, following the equations in 3.1. After some training sessions, these offsets will naturally reduce. But, when the user goes exceeds the range of motion, the system must visually restrict its movements, so that after some time, he/she will start performing the correct movements. The last case that may happen is that the user performs the required range and the system will only have to mirror its movements and let the level of challenge do its job.



(a) Insufficient. **(b)** Excessive. **(c)** Adequate.

Figure 3.5: Possible scenarios for user's range of motion.

$$\begin{aligned} \text{Left offset} &= \frac{A - O}{A' - O} \\ \text{Right offset} &= \frac{B - O}{B' - O} \end{aligned} \tag{3.1}$$

3.5 Graphical User Interface for Patients

The user interface shown in figure 3.6 was designed for patients to play games. It allows them to choose the starting level of difficulty and velocity of the game, as well as the buttons or gestures that must be performed to complete the requested tasks. The default settings for the level of challenge and velocity correspond to the therapist's advice. Besides, the buttons of the controller are presented on the right side of the interface, aiding patients to choose them. Then, the patient just has to choose whether the session should be on virtual reality or not, and hot the ”Começar” button.

The area marked by the blue rectangle will change accordingly to required actions for each serious game.

3.6 Developed Serious Game: VR Tetris

In order to achieve the aforementioned goals, it is necessary to have patients perform appropriate rehabilitating movements while also maintaining both purpose and motivation. This is achieved in the form of a game, which must be simple and at the same time be challenging enough to keep patients engaged. As such Tetris, a puzzle video game widely known across the world, was chosen as the game to be developed. It was originally de-

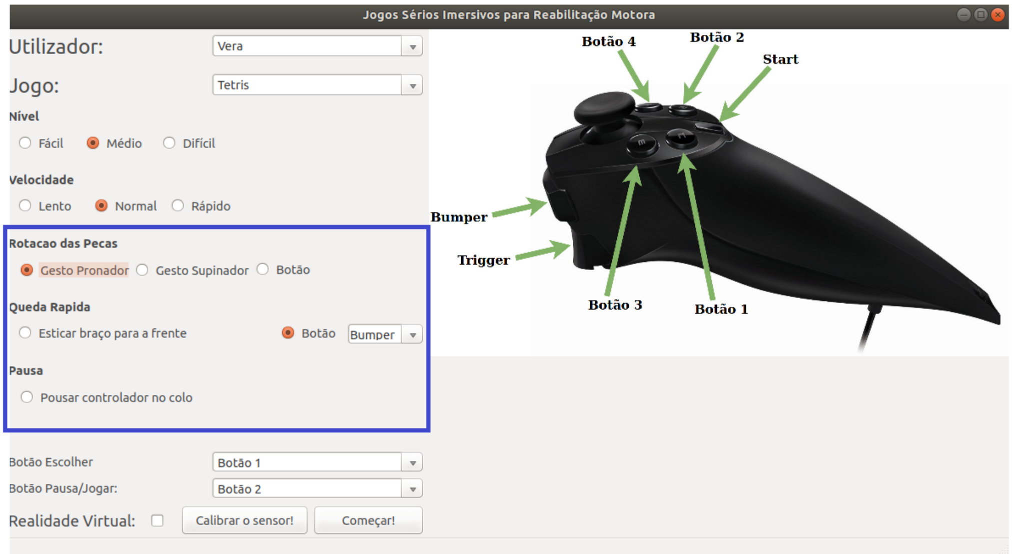


Figure 3.6: Graphical user interface to initialize the system.

signed and programmed by a puzzle-loving software engineer, Alexey L. Pajitnov, who created the first playable version in 1984. This video game reached such levels of popularity among all ages, that many variants have been created and distributed across many different platforms, which permitted to continually engage and captivate players until today. Surprisingly, the name ”Tetris” has derived from the Greek numerical prefix *tetra-*, since all playing pieces have four segments, and tennis, which is Pajitnov's favorite sport [1].

The game's purpose is to score as many points as possible by stacking the falling pieces (*tetrominoes*) into complete horizontal lines inside the playing area. During its fall, the user must rotate and move them to find the most adequate position for scoring more points. As the user completes one or more horizontal lines without any empty spaces, they disappear from the scene, adding a certain amount of points to the user's score. But, as lines are cleared, the level increases and *tetrominoes* fall faster, making the game progressively more challenging and demanding even more quick actions. If these horizontal lines reach the top of the playing board and no other *tetromino* can fall, the game ends.

An academic VR version of this popular video game was carefully crafted for therapeutic purposes, enabling the execution of movements in the horizontal plane to strengthen patients' muscles, while having their cognitive activity and sensory inputs (vision and hearing) stimulated.

Figure 3.7: Oculus Rift DK2.

3.6.1 Game Scenario

Designing and creating engaging virtual environments help the users to fully focus their attention on the task they have to perform. Therefore, these virtual environments for games should be designed considering the user's point of view, the available space for performing the requested tasks and the placement of the objects within the virtual space.

The *Oculus Rift DK2* is resposible to show the virtual environment to the user. The game scenario presented in figure 3.8 is composed of the following elements:

1. A wooden matrix that corresponds to the playing area.
2. A metallic pad that guides the *tetrominoes* and highlights their final position in the playing area.
3. A model of the used Razer Hydra Controller that is close to the metallic pad.
4. The leaderboard that contains the latest global scores for the game.
5. A score board that reveals the current score during the game play.
6. A skybox that serves as a background for the game, creating the illusion of distant three-dimensional surroundings.

The main reason that the model of the controller is part of the scene is that it produces the feeling that the users are directly controlling the metallic pad. If they are not able to perform movements of bigger amplitude, the game will amplify them and visually represent them on the controller and the metallic pad. This means that the possible movements are seen by the users as the required movements, creating a feeling of accomplishment and therefore motivating them to perform more.

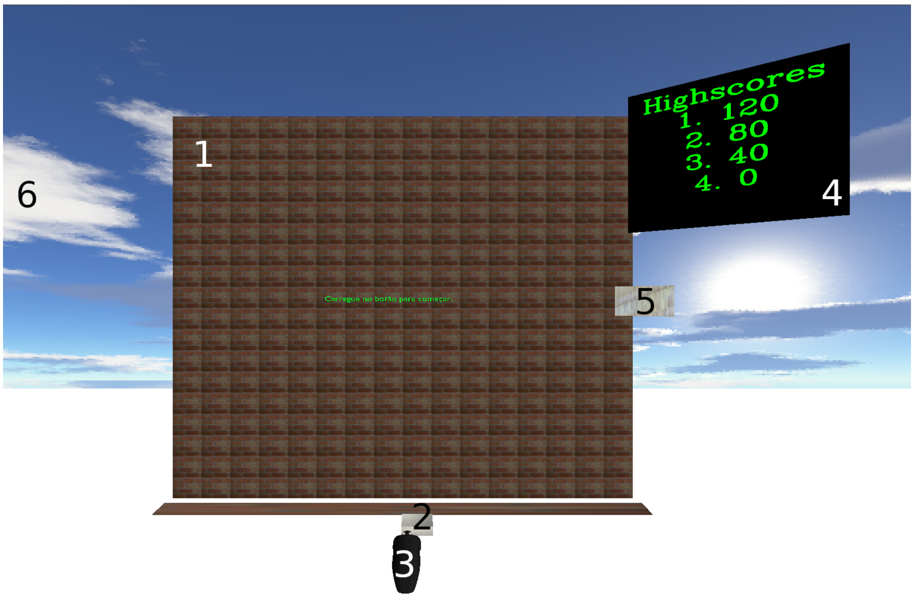


Figure 3.8: Game scenario.

3.6.2 *Tetrominoes* Generation, Rotation and Collision Algorithms

Seven standard types of *tetrominoes* appear during the game and all with different shapes and colors, as presented in figure 3.9, but they are all composed of four squared segments.

The difficulty of placing a piece depends not only on how fast it is falling but also on its shape. Thus, fitting shapes like O, I, J or L in advantageous positions are easier than the T, S, and Z. Playing only with O, I, J or L shapes allows users to have better scores as they are prone to complete more lines. Thus, having an algorithm that biases the shape of the piece to be one of those in the beginning, allows the game to be even more motivating since players will have higher scores.

The flow chart presented in 3.10 visually represents this algorithm. If the current level is lower than 3, it only produces Z/S/T shapes when all the previous four were O/I/L/J. If

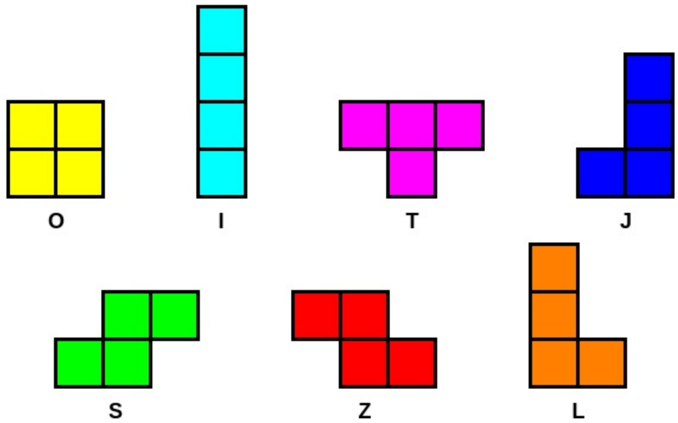


Figure 3.9: Different *tetrominoes*.

not, it will just create a *tetromino* with a different shape from the previous four.

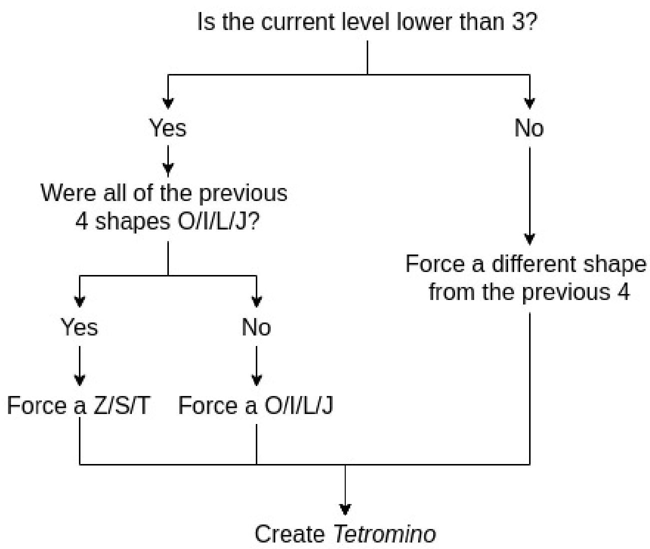


Figure 3.10: Flowchart for *tetrominoes* generation algorithm.

After the piece is created, it starts to fall and the player has to manipulate its position and orientation. The possible rotations for the pieces are presented in figure 3.11, and the player can achieve them by either pressing a button of the controller or rotating his/her hand like rotating a door's know. This gesture has more value to the patient's recovery since it involves the synergistic work of different muscles, which can be seen in [4]. The pronation of the hand leads to counterclockwise rotation, while the supination leads to a clockwise rotation.

A collision detection algorithm is responsible for checking the mobility of the pieces and

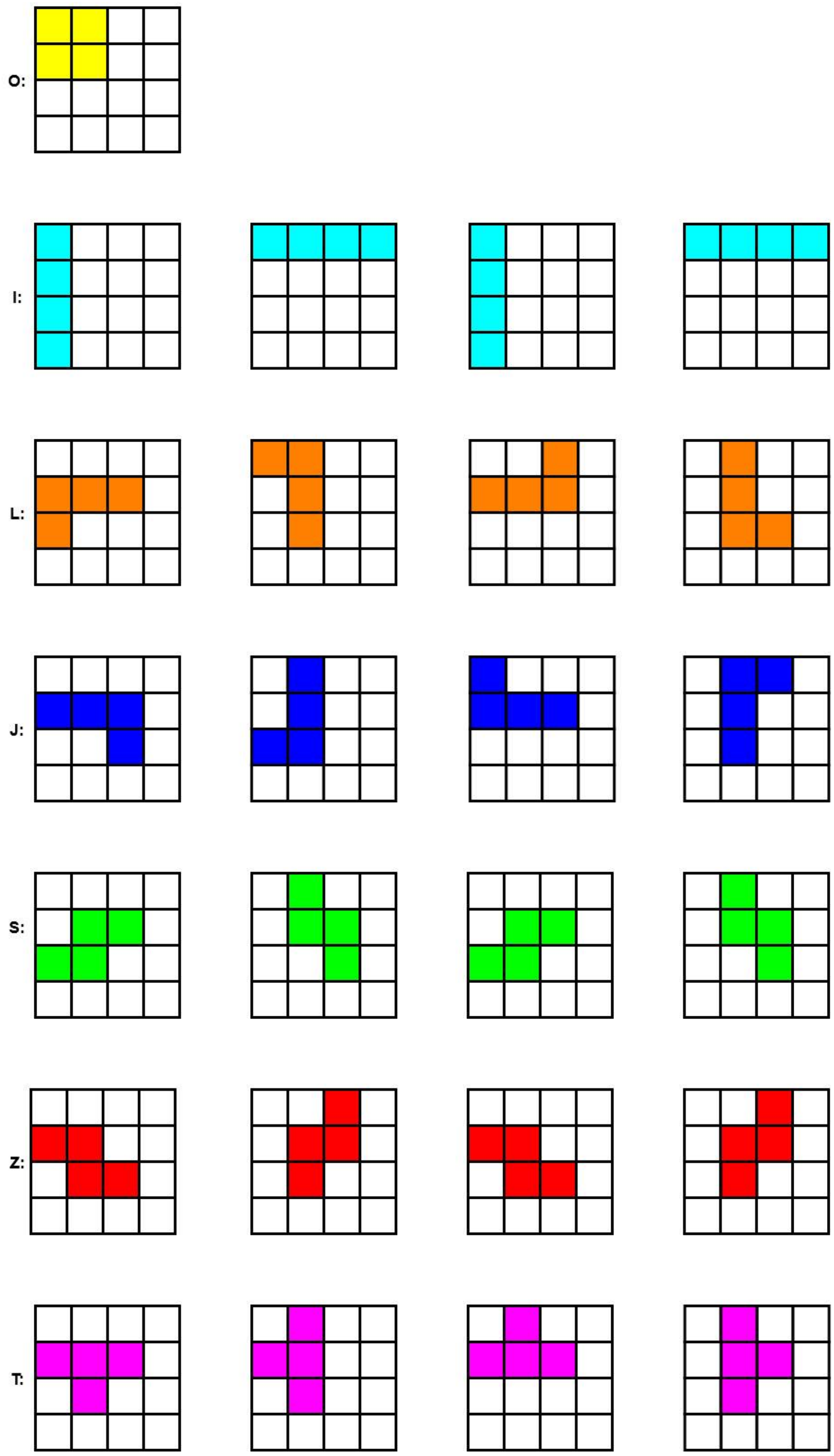


Figure 3.11: *Tetrominoes* possible rotations during the fall.

to alert the game's core if one of the following cases happens:

- The piece has reached the final falling position either because it is the bottom of the playing board, or the next falling position is fully or partially occupied.

- The user is trying to move left/right but the piece is already at its maximum left/right position on the playing board or the next left/right position is fully or partially occupied.

- The user is trying to rotate the piece but the next rotated position is fully or partially occupied, as visually shown in figure 3.12.

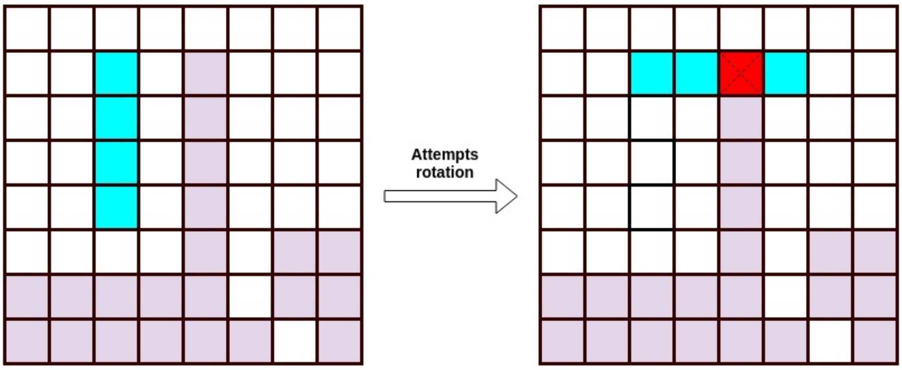


Figure 3.12: Collision detected when trying to rotate *tetromino*.

In addition, when the first case occurs, the player still has the same amount of time it takes to descend one row on the playing board to move the piece. It is referred as the lock delay, since the piece will lock after this delay, and visually shown in figure 3.13.

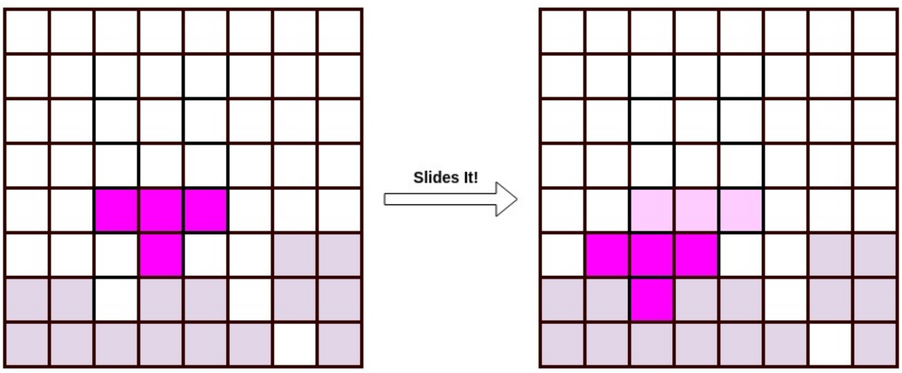


Figure 3.13: Lock delay for *tetrominoes*.

3.6.3 Difficulty Level Management and Failure Detection

This serious game is organized within different levels that have certain falling velocities of the pieces. Lower levels have a lower velocity and therefore are less difficult than the higher ones since the patient has more time to think about the action he/she wants to perform. But, as stated above, the shape of the currently falling piece is also relevant to increase or decrease the level of challenge. Thus, to manage these levels of difficulty a set of rules were defined:

- Current falling velocity is the time that a piece takes to descend one position in the playing board.
- The initial level of challenge is suggested either based on a therapist advice or by the most recent registered performance.
- There are unlimited levels of challenge, but once the player has reached a certain point, the falling velocity will be so high that it will be impossible to play.
- The current level of challenge depends on the current score and it is ruled by equation 3.2, where Current Score $\in [0,\infty[$ and Current Level $\in [1,\infty[$.

Given these rules, the current velocity is obtained from the current level of challenge using equation 3.3, where Advised Velocity $\in [1,4]$ and

$$\text{Current Level} = floor(\frac{\text{Current Score}}{1200} + 1) \tag{3.2}$$

$$\text{Current Velocity} = max(\text{Advised Velocity} - \frac{\text{Current Level}}{15}, 0.1) \tag{3.3}$$

Every game should not be either too hard or too easy. It should increase or decrease its difficulty according to the patient's performance, thus, being adaptive and dynamic to its inputs. In this way, if the patient is not capable of meeting the expected results during the game-play, the game should react to it and reduce its difficulty, preventing failure. Since it will most likely lead to quick frustration and disapproval of the game, the game should detect whenever the player is close and prevent it. Therefore, for lower levels, if the player is not capable of responding to the demanding difficulty, a mechanism is triggered and its actions are described below:

- If the player has many uncompleted lines with one or more free spaces, some of those lines might be broken, resulting in fewer points to add to the score:
  - Points for lines with 1 free space = 20;
  - Points for lines with 2 free spaces = 10;
  - Points for lines with 3 free spaces = 5;
  - Total number of uncompleted lines that can be broken during one game session = 5.
- If there is piece's occupancy percentage on the playing board higher than 70%, 3 bottom lines are immediately broken.

3.6.4 Leaderboard and Scoring Mechanism

The score encodes the user's performance during the game, which is considered to be a useful indicator for the therapist and one of the biggest motivational factors. Every human being is competitive by nature, which means that if faced with scores higher than his/her personal best, he/she will do everything to overcome them. As in the original game, the score only increases when lines are broken. Following the Original Nintendo Scoring System, the number of points obtained for breaking lines depends on how many are broken and on the current level of challenge (L) [6], as shown below.

$$
\begin{aligned}
\text{Points for 1 line} &= 40 * (L + 1) \\
\text{Points for 2 lines} &= 100 * (L + 1) \\
\text{Points for 3 lines} &= 300 * (L + 1) \\
\text{Points for 4 lines} &= 1200 * (L + 1)
\end{aligned}
\tag{3.4}
$$

3.6.5 Available Modes of Interaction

Given that different patients have different degrees of disabilities, a second mode of playing the game was built to achieve a wider range of players. Therefore, this VR version of Tetris provides two distinct modes of interaction with the same game elements

On one hand, the *Regular Mode* or ”*Modo Normal*” requests the player to guide the falling *tetrominoes* using the metallic pad placed on the bottom of the playing area as it was a ”magnet”. This means that the pad will attract the falling pieces to the same position that it is on the playing board. On the other hand, the *Timing Mode* or ”*Modo Temporizado*” allows the player to have a certain amount of time to choose between the most advantageous position for the *tetromino*, while it is still on the top of the playing board. During this time, the player moves the piece by directly moving the metallic pad and rotates it if necessary. As soon as the time runs out, the *tetromino* will immediately fall.

The main advantage of the second move over the first one is that the patient has more time time to decide the most suitable position for the *tetromino*, enabling also inexperienced users to play this serious game.

3.6.6 Game Play

The serious game is launched through the graphical interface and as soon as the user is ready to play, he/she presses a button. The diagram presented in 3.14 describes the possible paths that the patient may take while playing the game.

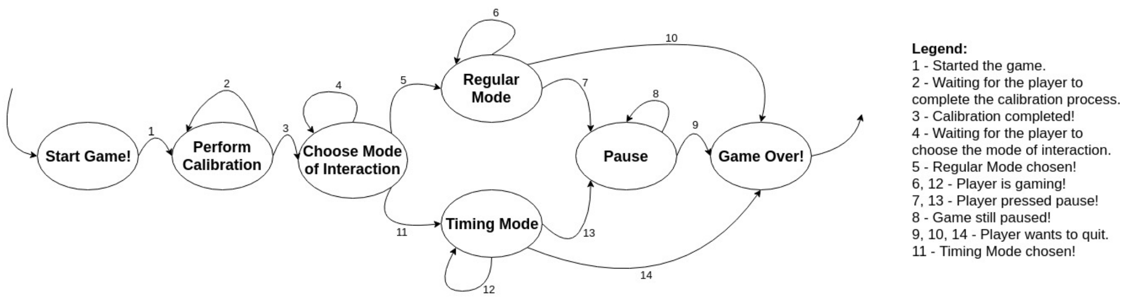


Figure 3.14: Flowchart that describes the game-play for Tetris.

It is easily observable that the first thing the patient will have to complete is the calibration as described in 3.4.1. After the calibration is complete, the two modes of interaction are displayed to the patient, as shown in figure 3.15.

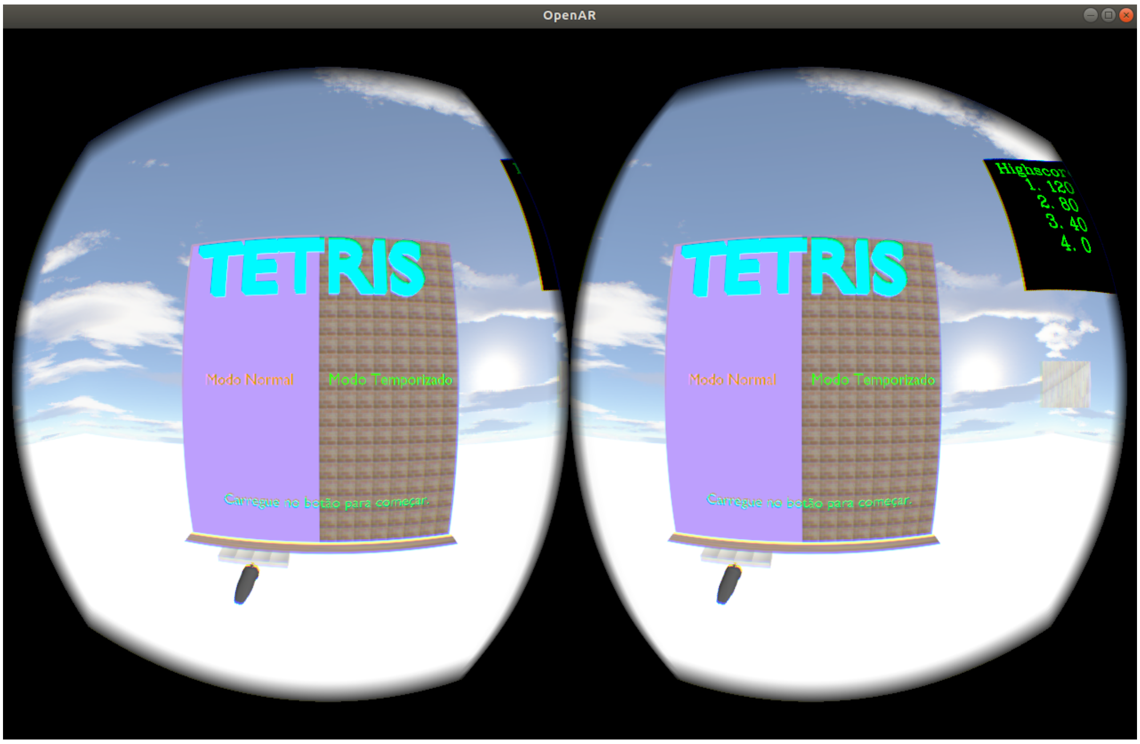


Figure 3.15: Scene to choose one mode of interaction.

Once a desired playing mode is chosen, the creation of the pieces begins, truly starting the game. As stated above, the patient will have to choose the most suitable position for the *tetrominoes*, either by guiding them throughout their fall (figure 3.16) or by moving them on top of the playing board (figure 3.17).

Sound plays a major role for providing a true immersive experience, being an excellent way to provide proper feedback to the user. Therefore, during the game play there is constant audio feedback that help the patient to perceive the actions that were completed successfully and the ones that were not, such as rotating a *tetromino* or breaking a complete line. Moreover, these sounds also alert players that new events were triggered, such as the generation of a new piece or new points have been added to their score.

While the patient is entertained by playing the game, several parameters are collected for later evaluation by the therapist. As different patients will have different performances, these parameters encode valuable information for later analysis, as seen in table 3.4.

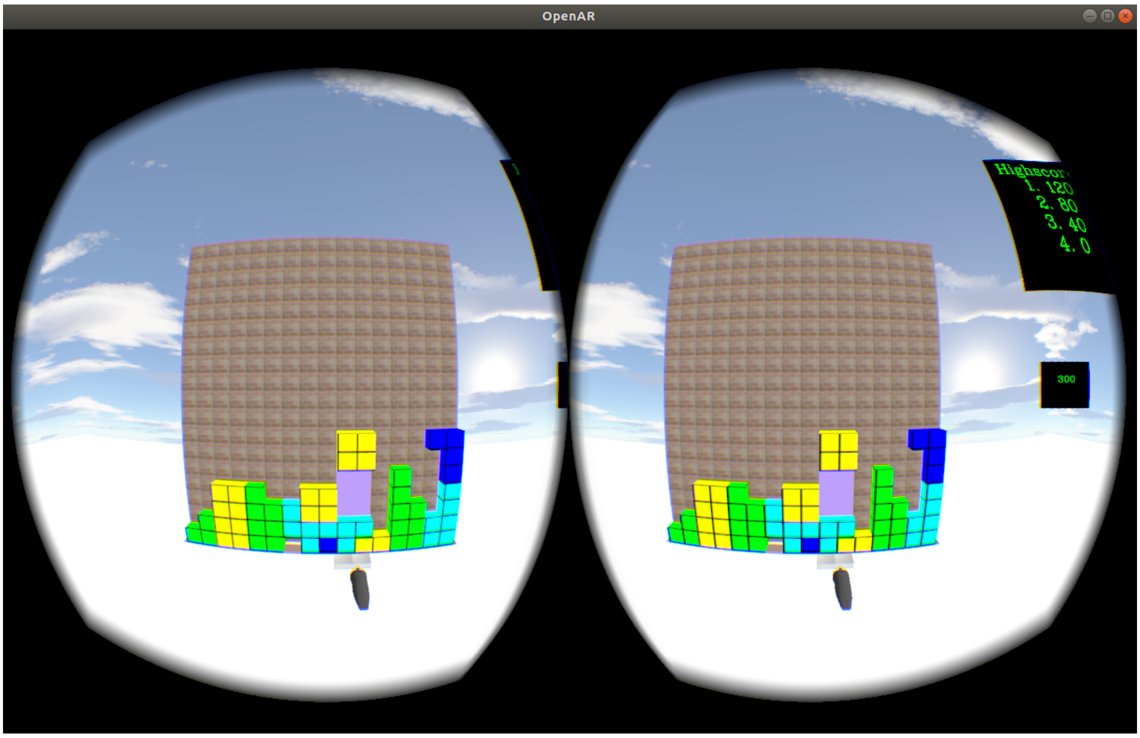


Figure 3.16: Example of game-play on Regular Mode.

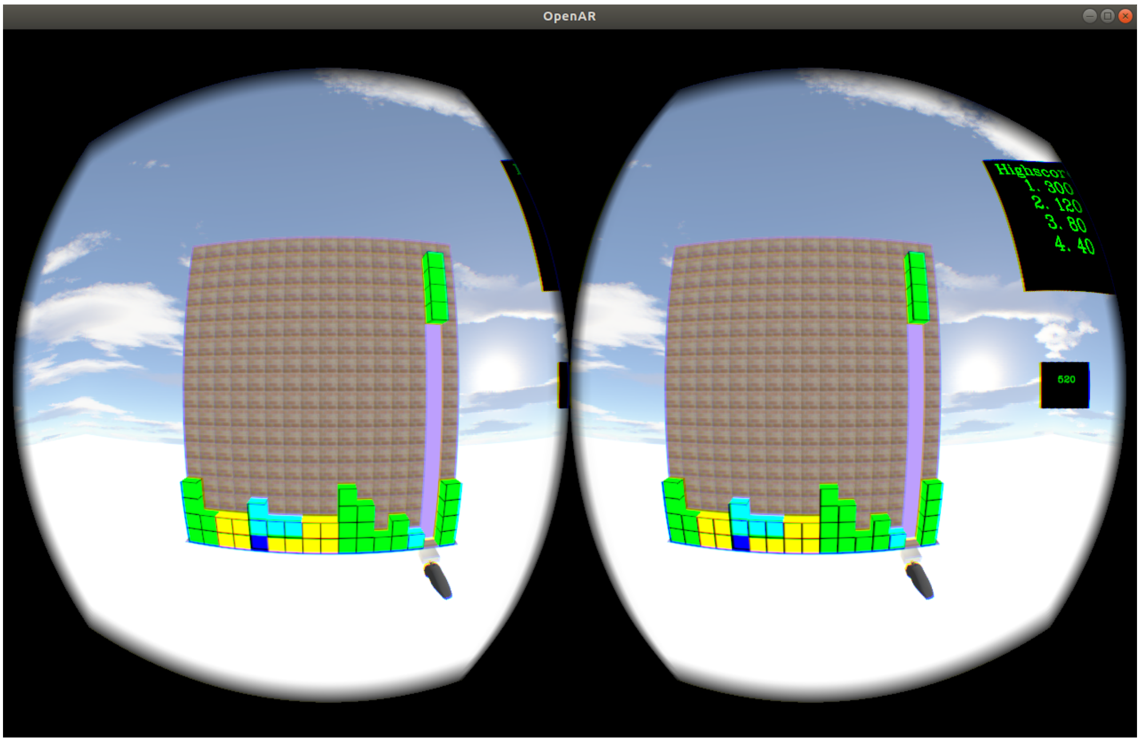


Figure 3.17: Example of game-play on Timing Mode.

In addition, when combined the distance covered with the number of changes in direction of motion, the therapist can better assess whether the accuracy of movements and if they

Parameter	Description
Score	Higher scores are linked with better performances during the game.
Final Level	Higher levels are linked to greater challenges, which require faster decisions and faster visuo-motor coordination.
Played Time	Longer sessions mean that patients performed their training for a higher amount of time.
Distance Covered	Greater distances covered with the affected limbs mean that their muscles were more used and in turn more stimulated.
Changes in Direction of Motion	Greater number of motion inversions may suggest inaccuracies in movements or that they were performed without objectives.
Initial Amplitude of Movements	Is the result of the calibration process. Considered to be extremely important to understand patient evolution over time.
Virtual Reality	Virtual Reality sessions mean that the patient's vestibular system was more stimulated.
Interrupted	Interrupted sessions may suggest that the patient felt uncomfortable playing the game, became ”lazy” or became unmotivated.

Table 3.4: Parameters regarding patient's performance collected during the game play.

were performed with objectives.

When there is no more space left to place the *tetrominoes*, the game ends by showing the ”Game Over” message and the final score to the player, figure 3.18. But most importantly, the parameters shown above are carefully arranged and saved in a local file.

The patient will now leave the game, deciding whether to play again or not, coming back to the graphical interface. At this point, the local file is read and the information is uploaded via Internet to the *RehabGames* database, to be displayed in the developed tool presented below in 3.7.

3.6.7 Visual and Cognitive Stimulation

As stated in 2.1, patients may also suffer from vision problems as a consequence of stroke, specifically visual field loss or visual processing issues, as well as cognition disorders. They may improve over time, as their brain recovers from this traumatic incident, but visual and cognitive stimulation is very important to aid their recovery.

Special attention was paid to the placement of the objects in the space in such a way that

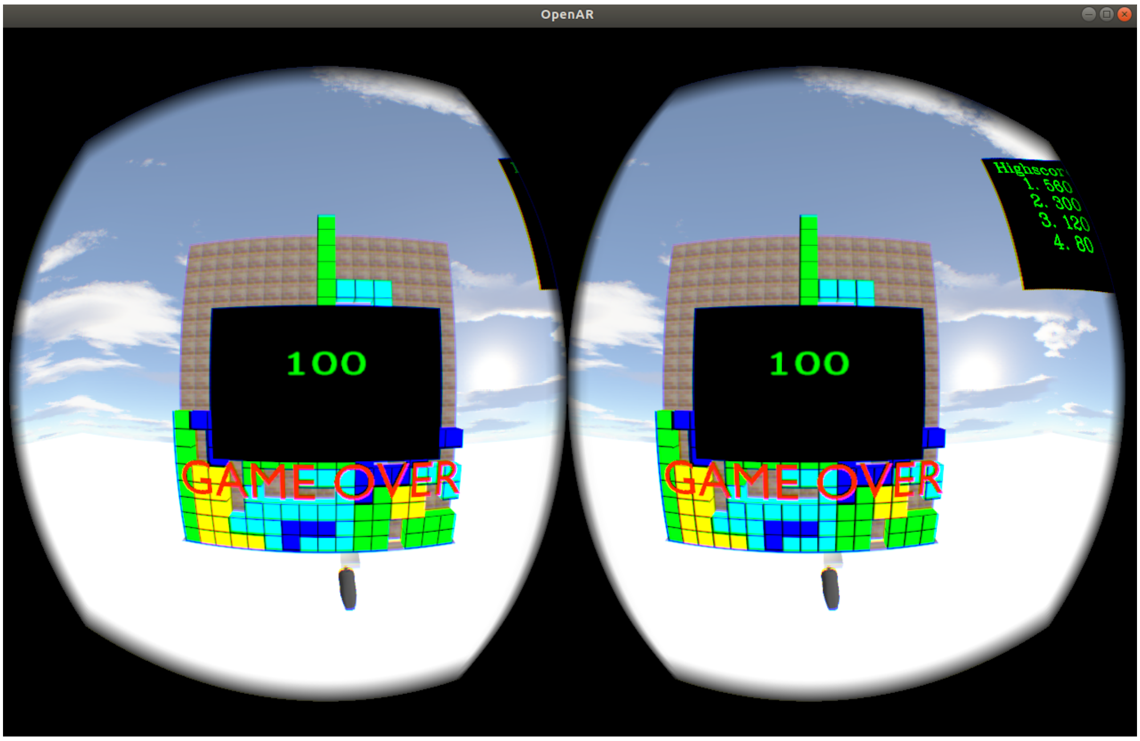


Figure 3.18: Game over.

patients will look involuntarily to both sides of their visual field in a systematic way, as a result of exploring the scene. To this purpose, a variant was introduced in the game by changing the distance between the playing area to the user's point of view. When the playing board is near, patients will have to rotate their heads, even more, to see where the shapes are coming from or to guide them. This forces them to look on both sides of the visual field. While if the problems are more severe, the distance is bigger, and fewer movements are required. It depends on the stage of recovery of the user.

Even though Tetris may not be considered the pinnacle of cognitive paradigms, it still represents a challenge to understanding the interaction between perception, action, cognition and decision making [43]. Moreover, as the game can be played either in a screen or in virtual reality, it also stimulates the patients' 2D/3D visuospatial skills as they are using them in order to find the most suitable position for the *tetromino*.

3.6.8 Reaction Time

Increasing the fall velocity of the *tetrominoes* over time not only reduces the possible boredom caused by monotony but also demands lower reaction times and faster limb movements. Therefore, as patients begin their recovery process, they should start with lower fall speeds, easing their task. But most importantly, they should start by playing this serious game using the *Timing Mode*. As the rehabilitation evolves in terms of the amplitude of gestures, perception, visual field and reaction times, the velocity should clearly be increased. This will enable patients to improve their concentration over time, as well as their visuomotor coordination and cognitive levels.

3.7 Patients' Tracking Tool - An interface for Therapists

An online back-end application has been built so that therapists can visualize their patients' progress over time: `https://orion.isr.uc.pt/~brunoferreira/RehabGames/`. The main objective is for therapists to keep track of how often or how good their patients play the recommended serious games.

Figure 3.19: Landing page of the *RehabGames* website.

Each therapist must login in order to be redirected to the *therapist's area*, presented in figure 3.20, which allows them to view all the patients and serious games existing in the database.

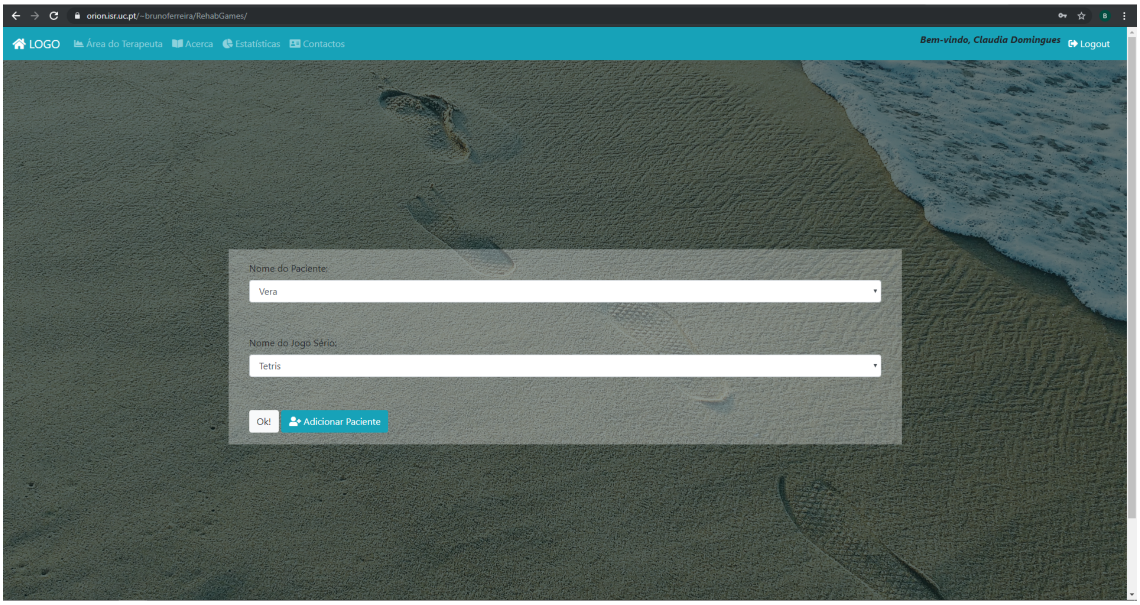


Figure 3.20: Therapist's area on the *RehabGames* website.

After choosing the patient and the serious game that they want to visualize, they enter the *patient's area*, where they can view different graphics concerning the parameters presented in 3.4 .

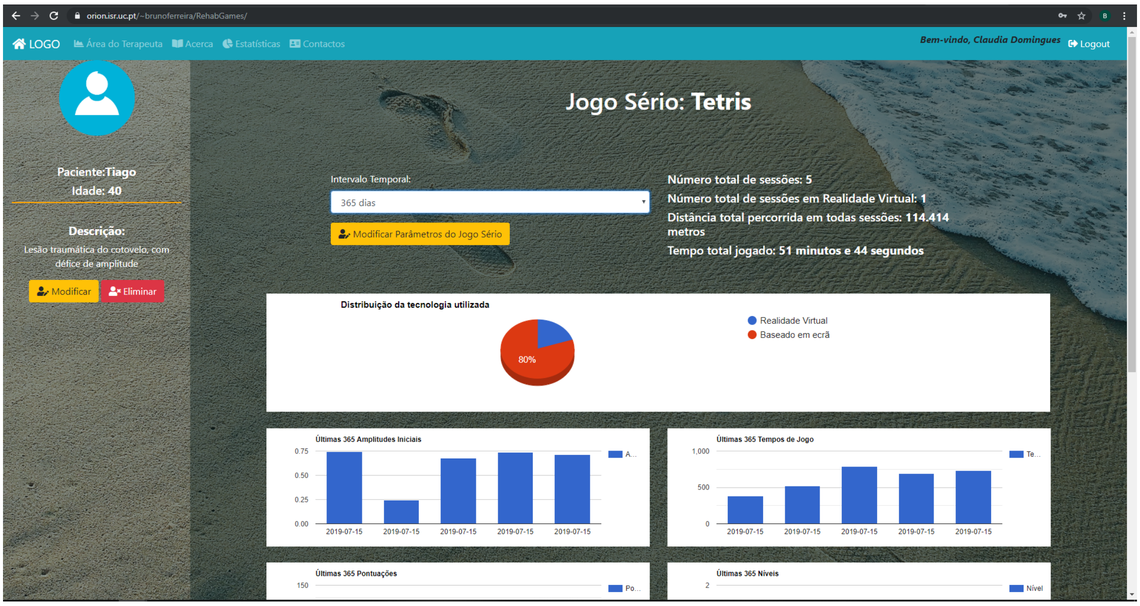


Figure 3.21: Patient's area on the *RehabGames* website.

Moreover, the website allows therapists to modify the game's parameters based on patients' evolution, update patient's information or even remove a patient from the database. Figure 3.22 shows some screen-shots taken during the use of a mobile phone to access the website.

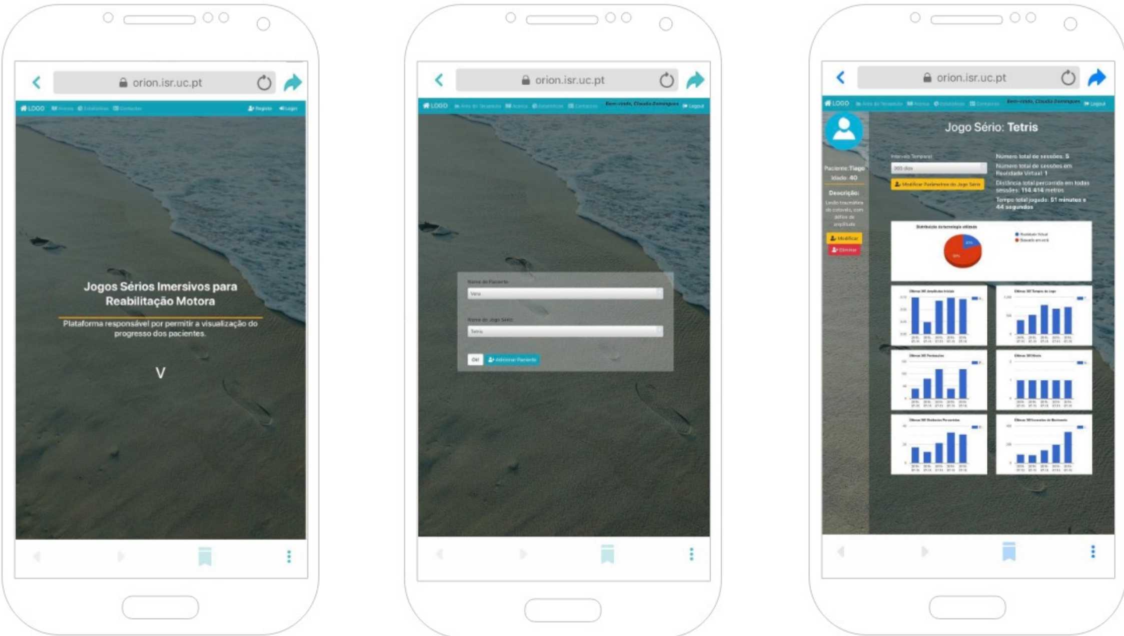


Figure 3.22: Mobile view of the *RehabGames* website.

4

Results and Evaluation

This section aims to present the results obtained after the development of the overall system, by showing and explaining a pilot study that was carried out in a local rehabilitation center, Caritas Diocesana de Coimbra [3].

4.1 Prior Evaluation by Therapists

Before testing the system with patients and discovering its usability in real cases, it is necessary to obtain the first form of validation among the therapists. These health professionals tested and evaluated the proposed system, focusing on the developed serious game, in order to find if it meets the prior requirements, being safe for their patients, as well detecting any sort of flaw that may compromise its use.

Their feedback was very positive, saying that the system was adequate for its intended purpose, adding that it would be quite easy to install in the available space. The calibration process that has to be completed before starting to play the serious game has been marked correct. In addition, they stated that therapies can really benefit from the advantages of VR, as they allow to stimulate the patient's vestibular system and their visual field. Thus, it was possible to perform the pilot study described below.

4.2 Pilot Study

A pilot study was carried out under the supervision of a therapist, with the main purpose of assessing the usability of the developed system prior to a larger study, while gathering vital information in order to improve the system's efficiency and quality. When conducting such as test, along different days, deficiencies in design and assumptions will be naturally discovered, as well as the project's potentials [48].

The participants on this pilot test were 40% female and 60% male, figure 4.1, with ages ranging from 30 to 90 years, figure 4.2. As most of the patients have handicaps that differ from each other, an heterogeneous group was formed, as shown in table 4.1.

Figure 4.1: Gender distribution of participants.

A brief explanation on some of the clinical disorder presented in table 4.1 is detailed below:

- Limb-girdle muscular dystrophy (LGMD) is a term for a diverse group of disorders caused by disease gene and inheritance. It usually manifests as weakness and wasting of the muscles in the arms and legs. The proximal muscles (the ones that are closer to the body) are the most affected, specifically the muscles of the shoulders, upper arms, pelvic area and thighs.
- Huntington disease is considered to be a progressive brain disorder that causes uncontrolled movements, emotional problems and loss of thinking ability (cognition).

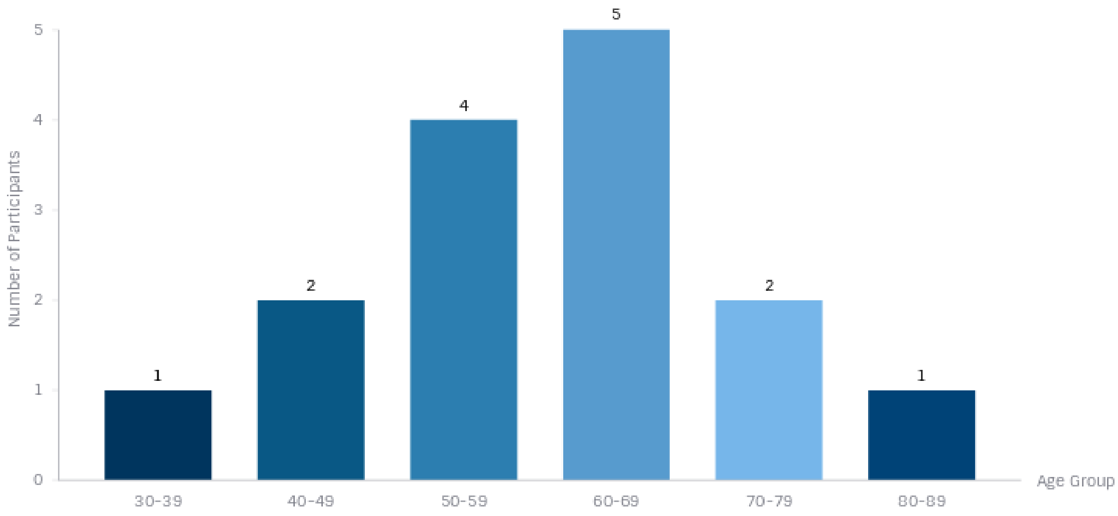


Figure 4.2: Ages of participants.

Patient Number	Gender	Age Group	Clinical Disorder
1	Female	50-59	Limb-Girdle Muscular Dystrophy
2	Female	50-59	Huntington Disease
3	Male	30-39	Traumatic Joint Injury with Amplitude Deficit - Elbow
4	Male	40-49	Spinal Cord Injuries & Paresthesias in Limbs
5	Male	60-69	Sequelae of Stroke (Left Side of the Brain)
6	Female	70-79	Brachial Plexus Injury
7	Male	60-69	Tumor in the Brain that affects Muscle Tone
8	Male	50-59	Primary Lateral Sclerosis
9	Male	60-69	Paraparesis
10	Male	60-69	Sequelae of Stroke (Right Side of the Brain)
11	Male	50-59	Sequelae of Stroke (Right Side of the Brain)
12	Female	40-49	Multi Strokes
13	Female	80-89	Lacunar Stroke (Left Side of the Brain)
14	Male	70-79	Sequelae of Stroke (Right Side of the Brain)
15	Female	60-69	Multiple Sclerosis

Table 4.1: Description of the different participants in the pilot test.

- Spinal cord injury may be referred as damage to any part of the spinal cord or nerves at the end of the *cauda equina* (the spinal canal), that often causes permanent differences in strength, sensation and other body functions below the area of the injury.
- Paresthesia in limbs is defined as an abnormal sensation of the body, such as numbness, tingling or burning.
- A traumatic brachial plexus injury represents sudden damage to this network of intertwined nerves that control movement and sensation in the arm and hand. Therefore, it may cause weakness, loss of feeling or loss of movement in the shoulder,

arm or hand.

- Primary lateral sclerosis (PLS) is a type of motor neuron disease that causes nerves within the brain to slowly break down, which makes them unable to activate the motor neurons in the spinal cord. These motor neurons are responsible for controlling muscles, thus it causes weakness in body's voluntary muscles, such as the ones used to control arms and legs.

- Paraparesis results in partial paralysis of both legs due to disrupted nerve signals from the brain to the muscles.

- Multiple sclerosis (MS) refers to an incurable disease that affects the communication between brain and the rest of body, since the immune system causes permanent damage or deterioration of the nerves. The impairments caused by this disease depends on the amount of nerve damage and which nerves are affected. However, some people with severe MS may lose the ability to walk independently.

The procedure used in the sessions of the pilot study is described below:

1. Briefly introduce the participant to what he/she is about to experience and take part of, as well as the technology that is going to be used.

2. Open the user interface and answer to any possible doubt. The participant should be able to understand its purpose and be able to initialize the system.

3. After initialization, the participant should play, following the advises of the therapist. If the therapist considers that the participant can use the Head-Mounted Display, ask patient if he/she needs help to place it properly and launch the game.

4. If he/she may feel uncomfortable with the experience, the procedure should stop immediately. Otherwise, allow him/her to finish the game without any kind of interruption.

5. When the participant reaches the end of the game or forced the end of the session, ask if he/she wants to play again and if it was pleasing.

6. In the end, fill a User Experience Questionnaire.

4.2.1 Analysis of the Results

The User Experience Questionnaire (UEQ) is commonly used to measure the user experience of interactive products, since it is a fast and reliable questionnaire [7]. In other words, it allows the researchers to understand both classical usability aspects (efficiency, perspicuity and dependability) and user experience aspects (originality and stimulation), using the 26 semantic differentials items that the user has to fill. The scales measured by the UEQ are described below with more detail and serve as a reference while evaluating the data:

- Attractiveness ("Atratividade") refers to the overall aesthetics of the product and how users are impressed by it.
- Perspicuity ("Transparência") reveals how easy it is to understand the product and get familiar with it.
- Efficiency ("Eficiência") translates whether it is easy or not to use the product without unnecessary effort.
- Dependability ("Controlo") reveals the feeling of control during the interaction with the product and how predictable it is.
- Stimulation ("Estimulação") refers to the excitement and motivation produced on the user by the product.
- Novelty ("Inovação") translates the creativeness of the product and if it catches the interests of users.

These questionnaires were filled by the participants as soon as they finished playing the serious game, either by experiencing virtual reality or not. Table 4.2 and the pie chart on 4.3 show that there were more participants using the HMD.

Participant	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Experienced VR?	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes

Table 4.2: Technology used by each participant.

As there are not enough data to directly compare the usability between using the HMD or

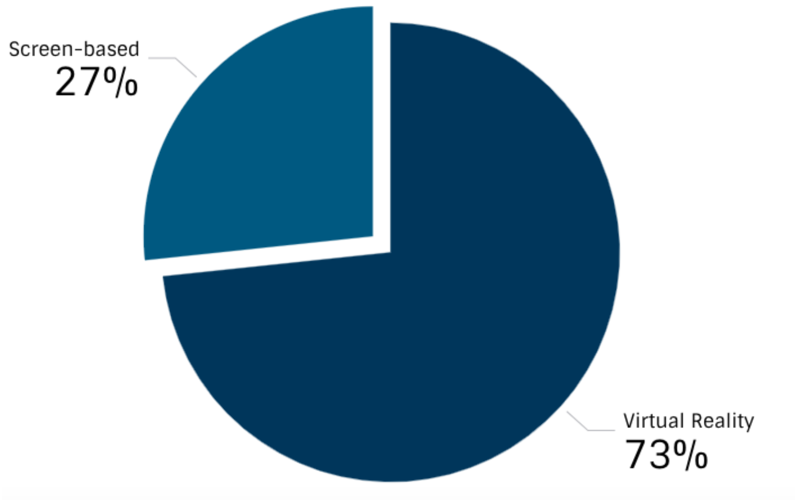


Figure 4.3: Distribution of the used technology.

not, the obtained results are analyzed separately using the *Data Analysis Tools* provided along the UEQ.

4.2.1.1 Without HMD

During the analysis of the questionnaires for this experience, it was noticed that one reveled several inconsistencies for the answers. Since this would mislead the results, that one was not considered, reducing the overall sample to three.

The answer distribution for the screen-based experience is shown in figure 4.4, where for each item (Y axis) there is a percentage of responses (X axis). It can be seen that the responses were mainly positive, with only two items (speed and predictability) with less good appreciation, which can be considered as related to the personal opinions about the system.

This positive polarized distribution reveals good values for the mean scales evaluated by the questionnaire, as shown in figure 4.5. As expected, the lowest value refers to the *Dependability* scale as it has the two least appreciated parameters.

The measured scale means are set in relation to existing values from a benchmark data set that contains data from several different products evaluation. As the most of the mean

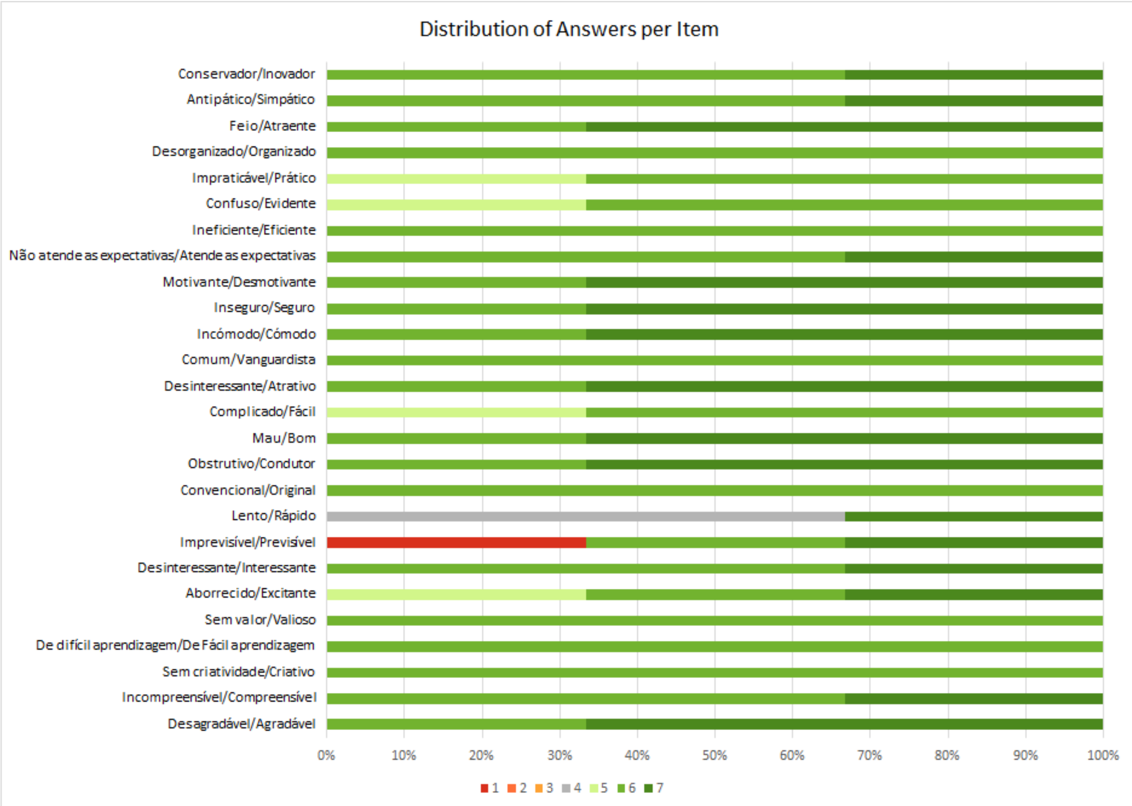


Figure 4.4: Answer distribution for the screen-based experience.

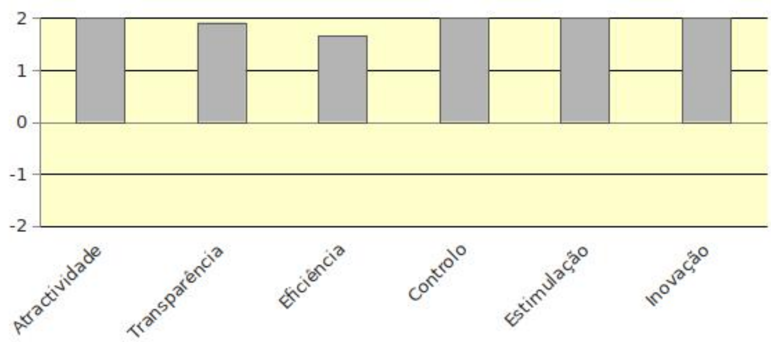


Figure 4.5: Means of the scales for the screen-based experience.

scales of the benchmark presented in figure 4.6 are excellent, it allows to infer that using the system during a screen-based experience is considered to be valuable and suitable for the patients.

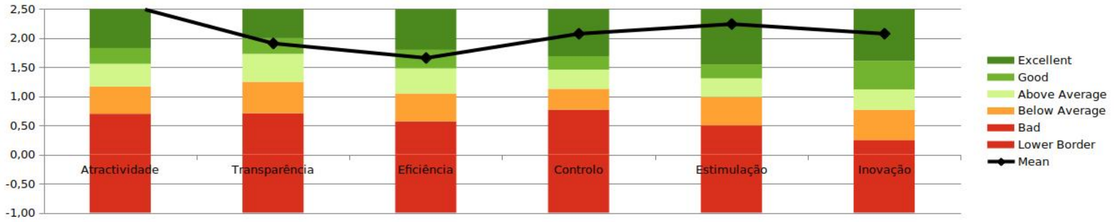


Figure 4.6: Benchmark for the screen-based experience.

4.2.1.2 With HMD

For the VR-based experience, the number of participants is eleven, which is a bigger sample than the previous one and will naturally lead to a wider amplitude of answers for the same items. This phenomenon is revealed by answer distribution in figure 4.7. Still, the distribution focus more on positive answers than the negative ones.

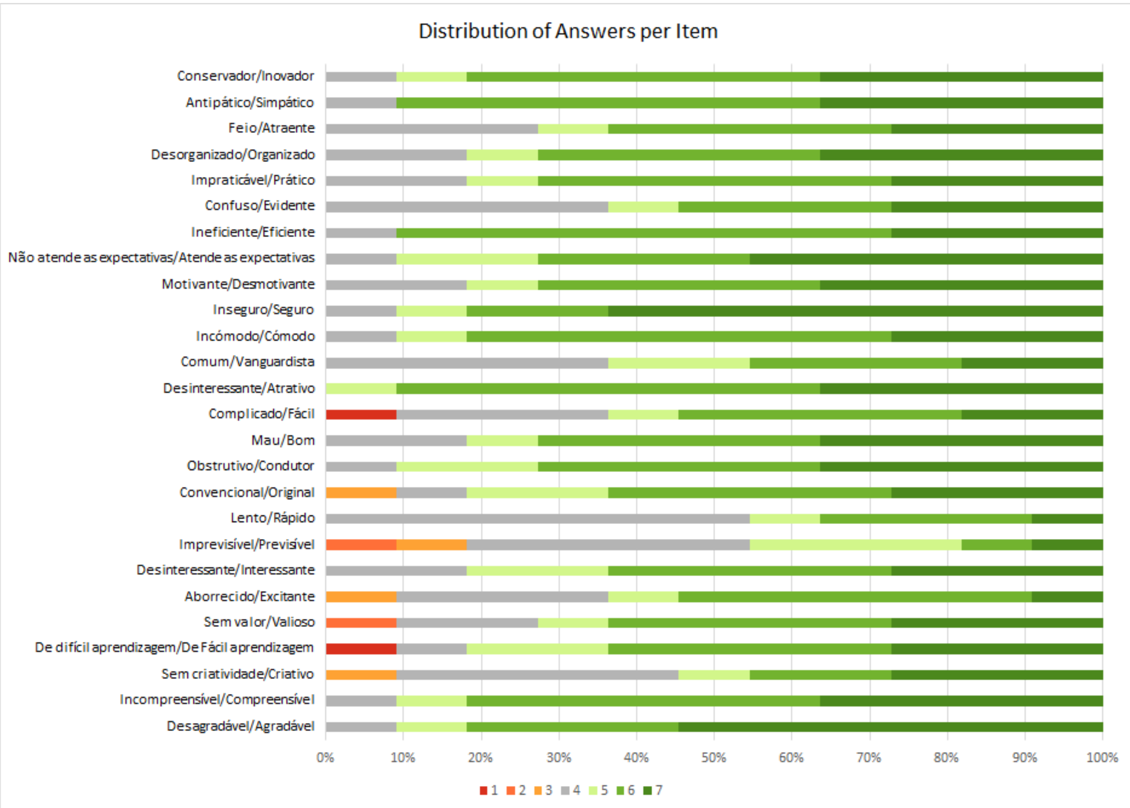


Figure 4.7: Answer distribution for the VR-based experience.

Although there are some answers not so good for the items ”Complicated/Easy”, ”Unpredictable/Predictable”, ”Boring/Exciting”, ”Inferior/Valuable” and ”Dull/Creative”. However, each of them belong to different scales, and therefore do not influence so much the mean scales presented in figure 4.8. These mean scales reveal that those negative answers were not frequent among the questionnaires.

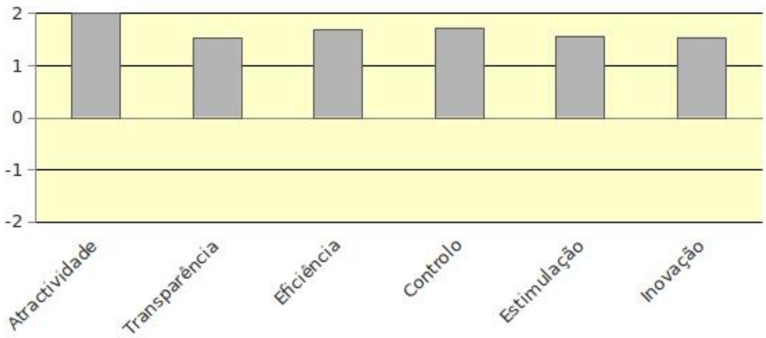


Figure 4.8: Means of the scales for the VR-based experience.

Finally, the benchmark presented in figure 4.9 shows that there are more good results than excellent results. Yet, given the bigger sample that tested the system using the HMD, the results are still above the expectations. In the end, the overall results suggest that the system can indeed be used in clinical environments, and are suitable for patients with different impairments and stages of recovery.

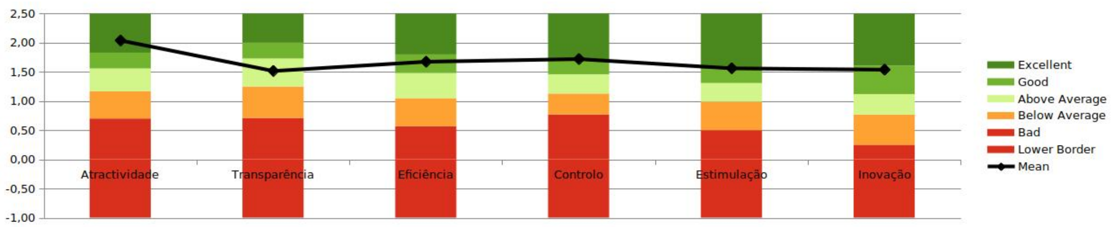


Figure 4.9: Benchmark for the VR-based experience.

4.3 Results of Patients

The results obtained by patients playing the serious game also form a fundamental part of this work. Figure 4.10 shows two of the participants in the pilot study playing the VR version of Tetris during their rehabilitation therapy. Although the angle of the photograph do not allow to visualize their happy faces, both were very motivated when playing.

This engagement and motivation to play the game can be inferred by table 4.3, from the number of times that patients played the game, as well as the total time they spent playing.

Figure 4.10: Two patients playing the developed serious game in virtual reality.

Other important aspect to mention is that the mean initial amplitude is different along the table, which confirms that the game can indeed be played by different patients. Although the maximum level and score obtained for each patient is relatively low, it should be noted that the vast majority of them have never played Tetris before and their experience with technology is very low.

The total distance covered by the affected limbs of the patients is 385 meters and 65 centimeters. Considering that a football field has a perimeter of 340 meters, it can be inferred that they performed sufficient therapeutic exercise for a complete lap around the field. Also, they played the serious game for about 431 minutes, enough for completing five football matches.

During the different days of testing, patients also gave their opinion regarding the serious game and the overall system, which were written down some of the words they used. These words were organized by the highest number of occurrences and presented visually in figure 4.11.

Patient #	# Plays	Mean Initial Amplitude (meters)	Total Played Time	Total Distance (meters)	Max Level	Max Score
1	7	0,500	20 min 26 s	24,17	1	80
2	8	0,329	44 min 44 s	32,76	1	0
3	5	0,621	51 min 44 s	114,41	1	120
4	4	0,358	18 min 50 s	29,81	1	0
5	4	0,247	5 min 42 s	5,03	1	0
6	5	0,543	27 min 24 s	20,03	1	0
7	3	0,546	17 min 27 s	10,86	1	0
8	3	0,762	17 min 14 s	21,93	1	0
9	3	0,635	18 min 6 s	26,29	1	0
10	5	0,434	22 min 31 s	19,36	1	100
11	3	0,409	11 min 30 s	8,78	1	0
12	5	0,490	32 min 24 s	23,23	1	200
13	6	0,389	45 min 46 s	27,90	1	100
14	5	0,249	78 min 55 s	24,50	1	400
15	5	0,421	18 min 52 s	15,95	1	0

Table 4.3: Results for the parameters collected during the gaming sessions of the patients.

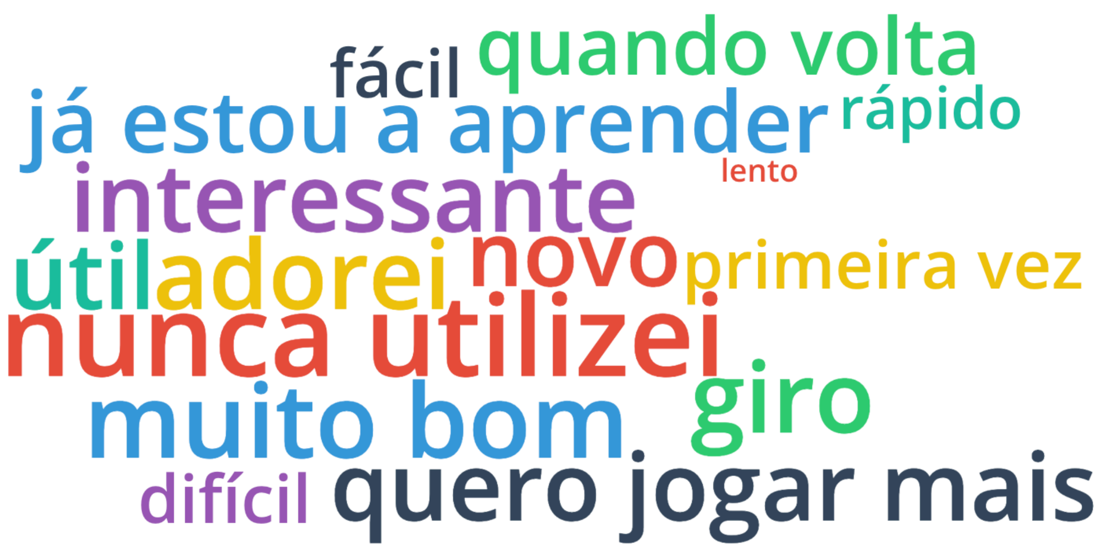


Figure 4.11: Some words used by participants.

5

Discussion

During the execution of the pilot study, four participants weren't able to use HMD because of their condition, revealing the importance of having an option that allows playing whether with HMD or not. Since the clinical space, where patients work for their rehabilitation, has a large flow of people, it is quite easy to get distracted. But, it was noticed that the patients who used the HMD focused much more on the tasks they had to perform. Although it is a small pilot study and related to the usability of the system in real cases, the results are promising, revealing that it was accepted with satisfaction by all those who experimented. The 15 participants represent 75% of the clinical cases that pass through this clinical space to perform the necessary training for their recovery. And yet, participants reported that they would like to play more often and that it was a pleasant and motivating experience. Thus, allowing patients to play over several sessions over time would be important to find out how really a system like these would help their evolution.

Therapists mentioned that the serious game developed was crucial for the development of skills such as attention/concentration, coordination, and movement control, validating the requirements set out in Chapter 3 on visual, cognitive stimulation and reaction time. They even noticed that the patient with Huntington's disease was having more control over her movements in an attempt to meet the objectives of the game. Besides, the fact that there were different participants with different amplitudes of motion, as shown in Table 4.3, reveals that the game can indeed adapt to their difficulties. Moreover, the different values obtained for the initial amplitudes of each patient shows that by having this pleasant experience they may improve their condition over time, specifically the ones with stroke sequelae.

This serious game was evaluated as perfectly adequate for patients with mild to moderate muscle tone. However, patients who have muscle tone assessed as important may still play the game with the help of their less affected arm/hand or support that eases movement. One can imagine inclined support or even one as a kind of ”skateboard” that allows the affected upper limb to slide on a board and using brakes on the wheels to increase or decrease the resistance to movement. On the other side, increasing the difficulty of movement also increases the required effort to perform it, which may be suitable for patients within more advanced stages of recovery. But, for early stages of evolution, support that reduces this effort to perform the movements should be used, thus promoting motor rehabilitation.

As the game was designed to enforce the use of the arm and shoulder to perform the required movements, some variations may be applied to it to allow patients to use different muscles. These variations are described below:

- In Timing Mode, instead of having the *tetromino* falling after a certain amount of time, the patient could ”touch” it, promoting vertical movements.
- In Regular Mode, instead of guiding the fall of the *tetromino*, the player may drag the piece from the top of the board to the bottom, which will also force patient to perform vertical movements.
- For both modes, therapists may ask patients to perform the calibration process in different positions, such as holding the controller in a higher position, which makes it an uncomfortable position to play.

Another variation to enhance difficulty and allow them to develop better decision-making skills is to have two pieces in the scene: after generating the *tetromino* and it begins to fall, it should automatically generate another one.

For the website, thought was given to creating an alert system that would allow therapists to receive notifications about patients’ activities. Soon when patients take the system home, the therapist would receive an alert regarding the case of patients not performing the recommended practice, or that the playing times are lower than expected. However, as therapists only confer patient information when they are with them, meaning that it is more important to implement other variations in the game.

6

Conclusion and Future Work

The work described in this dissertation aimed at the development of virtual reality serious games for upper limb rehabilitation. The gamification ingredients placed in this academic version of Tetris have made it a motivational game that provides a pleasant experience for patients with different impairments, undergoing rigorous and demanding therapies. To assess its usability in real scenarios, a pilot test was carried out at a local rehabilitation center.

The global feedback received, the analysis of the questionnaires filled out by patients, as well as the evaluation provided by the therapists shows that the system described in Chapter 3 excelled during this pilot test, accomplished every objective proposed. Also, the fact that the developed work is suitable for 75% of the people that through that clinic proves that it is indeed useful in the aid of the conventional motor rehabilitation therapies, showing promising results for further future work related to it.

One article and one demo have been accepted and presented at the *Experiment@ International Conference 2019 (exp.at'19)*. Author versions of these articles are included in the annexes of this document.

Although the work presented focuses on the development of serious games for rehabilitating patients' upper limbs, due to the modular design of the framework created, new games with different therapeutic purposes can easily be included in it. The given number of possibilities is huge. However, it is suggested that some of the aspects to be explored by these games should be more movements in the vertical plane, increased resistance to movement and fine motor skills, while continuing to stimulate both the cognitive and sensory part of the patient.

Introducing virtual avatars as form to represent the patients' bodies in the virtual environment may be also explored, since it would lead to higher levels of immersion, becoming a more realistic experience. The idea behind this is to have patients being transported to a complete different world, where they would see those virtual avatars as a ”better” or ”healthier” version of themselves.

In the future, this system should be taken to the rehabilitation clinic for a longer time scale, allowing to understand the impact of it during the patients recovery. Nevertheless, it should also be taken to home environments in order to explore its usability outside of a clinical environment.

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Appendix

- 3D Modeling a Controller
- User Experience Questionnaire - Portuguese Version
- exp.at'19 - Full Paper
- exp.at'19 - Demo

3D Modeling a Controller

Bruno Ferreira

Many game developers struggle to bring objects from the real world into the alternative realities, as often their 3D models whether are not available online, or they are, but are expensive. Therefore, there is a need for creating them, using a technique under the Computer Graphics area, which refers to the development of a mathematical representation concerning a desired object or surface - 3D modeling. This process can be achieved automatically or even manually, depending on the appropriate software used, such as *Blender*[1].

The modeling process begins with taking good reference photos at different views of the object (front, back, left and right side , bottom and top) in order to create an accurate model. These photos serve as a reference as soon as they are imported into the Blender scene, and are responsible for revealing the real world proportions of the object, i.e, the height, length ad width of its each part. Having wrong proportions will lead into a misleading representation.

A primitive shape is placed into scene, such as a cube, for adding the necessary detail in Blender's *Edit Mode*. This mode will alter its shape by dealing with individual elements of the object's mesh, until having an accurate representation of the object, as shown in figure 1. However, this new shape still doesn't completely model the real world object, which means that it has to go trough a sculpting process.

The Blender's *Sculpt Mode* deals with a certain area of the model using a brush. Under the region of influence of this brush, the geometry of the object may be manipulated in order to perfectly add the required contours or even add some particular parts of the real world object. After sculpting for a while, the created model begins to look like the real world object, as represented in figure 2.

Note that the computation power required to properly load a model is directly linked with the complexity of the model's mesh (more vertices, means more computation power). Thus, its mesh should be complete enough to have a realistic representation of the object, but at the same time as more simple as it can get in order for the application to run as smooth as possible.

Once the modeling process is finished, the model can be exported into different data formats, including collada file (.dae), meaning that it can be used among many different applications.

[1]Blender is a free and open source 3D creation suite.

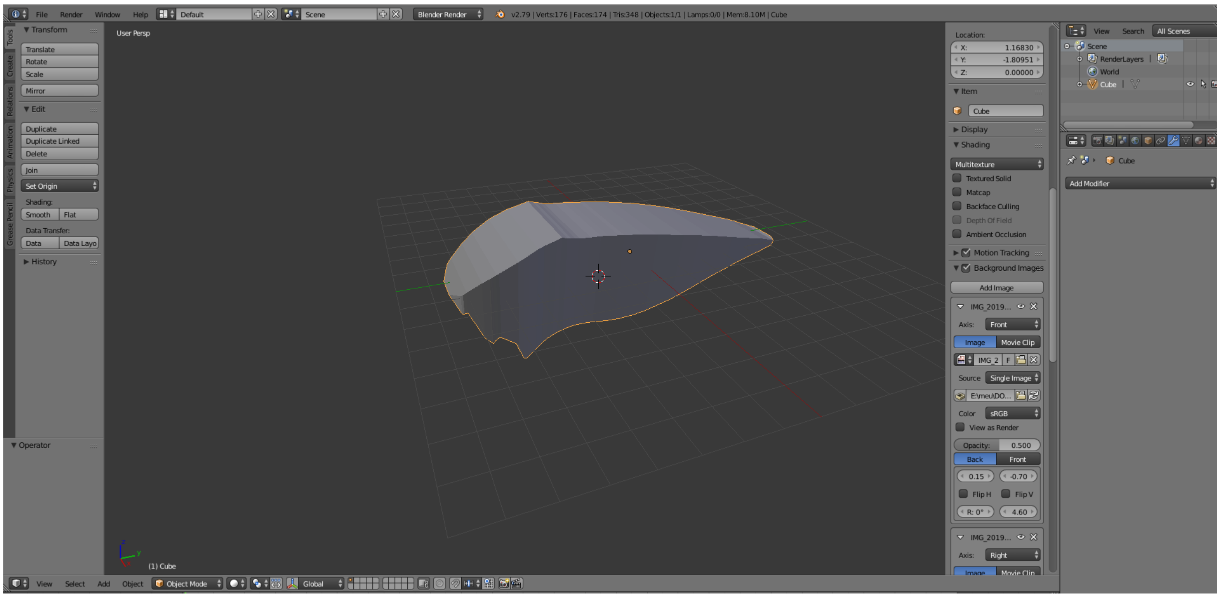

Figure 1: Primitive shape modeled to a similar representation of the object.

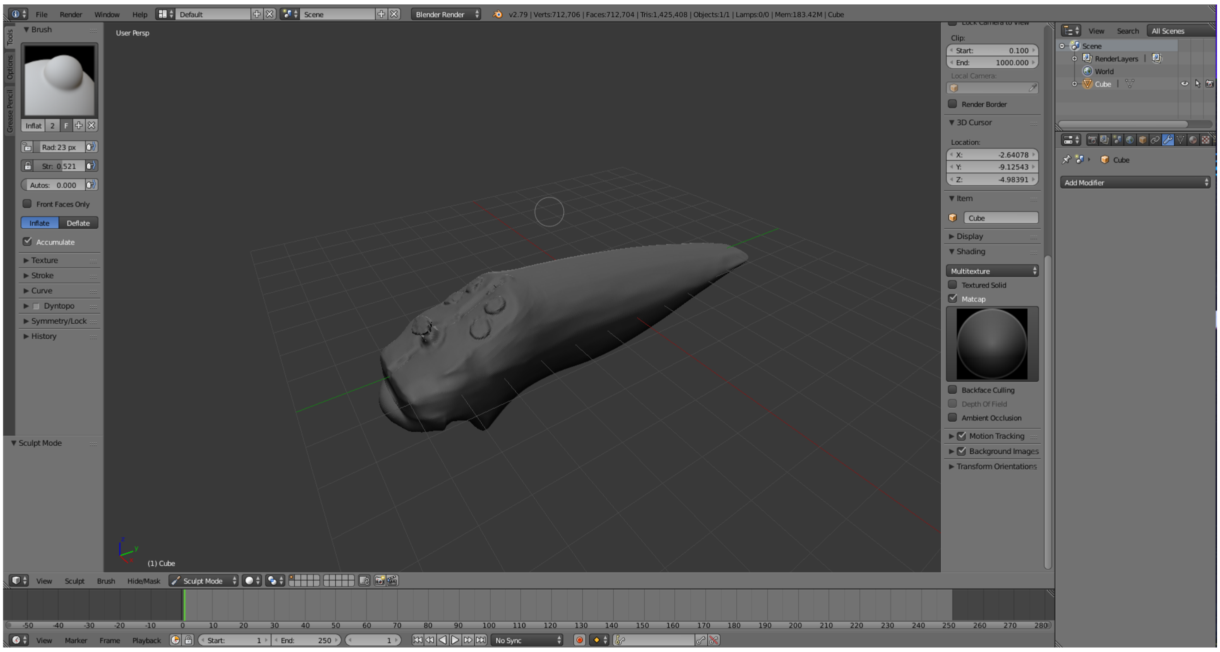

Figure 2: Sculpting the primitive shape into a more realistic representation of the object.

Por favor dê-nos a sua opinião.

A fim de avaliar o produto, por favor preencha o seguinte questionário. É constituído por pares de opostos relativos às propriedades que o produto possa ter. As graduações entre os opostos são representadas por círculos. Ao marcar um dos círculos, você pode expressar sua opinião sobre um conceito.

Exemplo:

Atraente	○	●	○	○	○	○	○	**Feio**

Esta resposta significa que avalia o produto mais **atraente** do que **feio**.

Marque a sua resposta da forma mais espontânea possível. É importante que não pense demasiado na resposta porque a sua avaliação imediata é que é importante.

Por favor, assinale sempre uma resposta, mesmo que não tenha certezas sobre um par de termos ou que os termos não se enquadrem com o produto.

Não há respostas "certas" ou respostas "erradas". A sua opinião pessoal é que conta!

Por favor, dê-nos a sua avaliação atual do produto em causa.

Por favor, marque apenas um círculo por linha.

	1	2	3	4	5	6	7	
Desagradável	○	○	○	○	○	○	○	Agradável
Incompreensível	○	○	○	○	○	○	○	Compreensível
Criativo	○	○	○	○	○	○	○	Sem criatividade
De Fácil aprendizagem	○	○	○	○	○	○	○	De difícil aprendizagem
Valioso	○	○	○	○	○	○	○	Sem valor
Aborrecido	○	○	○	○	○	○	○	Excitante
Desinteressante	○	○	○	○	○	○	○	Interessante
Imprevisível	○	○	○	○	○	○	○	Previsível
Rápido	○	○	○	○	○	○	○	Lento
Original	○	○	○	○	○	○	○	Convencional
Obstrutivo	○	○	○	○	○	○	○	Condutor
Bom	○	○	○	○	○	○	○	Mau
Complicado	○	○	○	○	○	○	○	Fácil
Desinteressante	○	○	○	○	○	○	○	Atrativo
Comum	○	○	○	○	○	○	○	Vanguardista
Incómodo	○	○	○	○	○	○	○	Cómodo
Seguro	○	○	○	○	○	○	○	Inseguro
Motivante	○	○	○	○	○	○	○	Desmotivante
Atende as expectativas	○	○	○	○	○	○	○	Não atende as expectativas
Ineficiente	○	○	○	○	○	○	○	Eficiente
Evidente	○	○	○	○	○	○	○	Confuso
Impraticável	○	○	○	○	○	○	○	Prático
Organizado	○	○	○	○	○	○	○	Desorganizado
Atraente	○	○	○	○	○	○	○	Feio
Simpático	○	○	○	○	○	○	○	Antipático
Conservador	○	○	○	○	○	○	○	Inovador

A Serious Game for Post-Stroke Motor Rehabilitation

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Abstract. Post-stroke rehabilitation should start as soon as possible, once the patient's condition is considered stable. As rehabilitation must be intensive and repetitive, this can lead to problems with patient motivation and engagement. This paper proposes an immersive tool that intends to aid the traditional motor rehabilitation therapies, in order to both motivate and encourage the patients to perform therapeutic exercises, by having them distracted from their handicaps. Since different people have different needs, the game dynamically adapts to the user, by increasing or decreasing its level of challenge. Following the proposed solution principles a serious game was implemented and evaluated with positive results.

Keywords: Serious games · Immersion · Virtual Reality · Embodiment · Engagement · Rehabilitation · Stroke.

1 Introduction

According to the *Stroke Association*, every two seconds, someone in the world suffers a stroke [2]. This means that someone will most likely remains with impairments such as balance loss, partial paralysis and/or reduced movement on one side of the body. Among the consequences of the stroke, the affected side of the survivor's body frequently manifests hypotonia [14]. Most stroke survivors tend to try to overcome the handicap in the affected limb, by overusing the healthy one. Thus, upon leaving the hospital, although patient's condition is considered stabilized, he/she still has a long way to go in order to recover his/her physical functions. This includes the execution of different physical exercises, which are crucial to overcome the attained condition.

Over time there have been many systems created and tested for motor rehabilitation, robotic devices to aid patient's mobility, and even video games that try to increase patient motivation during the exercise execution. In fact, video games have succeeded in attracting people of almost all ages and this has triggered the researchers attention to the possibility of using them as therapeutic tools [10]. To this purpose, and focusing on health application areas, some authors have found that virtual environments may be tailored to provide safe and custom-made training according to the patient's needs or abilities [5,11].

The work described in this paper is centred on the development of a low-cost virtual reality-based serious game addressed to stroke survivors who have to deal with one of the common consequences which is the loss of mobility in one arm. The proposed solution uses specific controllers to track the position and the orientation of the user's limb and an head-mounted display to provide the immersion sensations in the virtual environment.

2 Patient Condition and Typical Therapeutic Approaches

Typically, a patient after suffering a stroke, struggles to maintain the affected limb stabilized in any position, caused by *hypotonia*. Over time, it is common to have hypotonia replaced by spastic hypertonia (muscles becoming very rigid), complicating movement execution. This can lead to secondary complications, such as muscles and joints' contractures, pain and functional disorders, with abnormal postures and stereotyped moves which may lead to complete disuse of the affected limb [14].

The post-stroke rehabilitation protocols typically start with series of exercises for the arm muscles and progressively go towards fine control of hand and fingers. Despite the therapeutic purpose, these tasks are typically repetitive and boring as they do not provide any type of entertainment and the rehabilitation effects are not visible within a single session. In fact we may say, that it is indeed hard to design motivating physical tasks, especially for the initial sessions, given the limitations in the range of movements that can be performed by the patient.

Depending on the affected region of the brain, patients may also exhibit some vision problems, such as partial visual field loss, limitations in eye movements and vision processing problems. Visual field loss means that part of the information produced by the retina does not arrive to some layers of the visual cortex which have specific purposes. As result there may be blind zones, reduction of object or people recognition capabilities on all or part of the visual field, or lack of attention triggering (typically motion/change detection) in one region of the field of view [12]. Some of these problems tend to disappear with time, but others do not. In any case, developing some task that implies tracking of elements that cross the affected/non-affected frontier will help either as a stimulation for the faster recovery, or as a training for the person to develop alternative sensing and/or scanning strategies.

2.1 Physical rehabilitation and adherence issues

Upon leaving the hospital, patients are typically very limited in the range of movements they are able to perform autonomously, in particular with the limbs related with the affected brain region. It is well known that early physical rehabilitation is crucial for attaining good recovery results [16]. This rehabilitation process, which is frequently referred as motor re-education, must also comply with the degradation or alteration of sensory inputs due to some damage in sensory tracks or in upper cerebral areas.

Most stroke survivors tend to try overcome the handicap in the affected limb, by overusing the healthy ones. As this represents some reward, as upon success it represents less dependency, they tend to focus on that and forgetting the affect limb. As they may get more and more efficient in using a single hand and arm for most tasks, the result is that the affected limb becomes (almost) completely ignored at first and useless later. In these situations one common approach, but that is not necessarily well accepted, is to ask the patient to develop some tasks, with the movements and usage of the healthy limb physically constrained. This will force the use and focus on the limb to be recovered, and thus to promote the establishment of new neural pathways via the learning/training processes.

Although people are typically instructed to continue at home to perform the exercises with the affected limb, in most cases these are solely done in the presence of the therapist. This happens by the fact that there is only the long term possibility of some recovery. Wrongly many people tend to prefer to try to forget that handicap, instead of doing the necessary efforts for the recovery process. In sum, the lack of immediate reward leads, in most cases, to this lack of interest in continuing the exercises execution at home.

3 Designing post-stroke Rehabilitation Games

From the above, there is clearly an opportunity to explore the concept of serious games for rehabilitation therapies, in order to increase the engagement to some playful therapeutic practice [6]. This approach attempts to provide some pleasure and motivation to the patient while playing with it. Being more motivated, it is expected that this will increase the number of executed exercises per session and the number of sessions performed at home and therefore increase the odds of attaining the expected therapeutic success [1,13,15].

Naturally the design of any game for post-stroke rehabilitation must follow the same objectives and principles of the traditional therapeutic approaches. While adapting to the specific limitation of each patient, besides his/her condition, it should provide an enjoyable experience and avoid any type of frustration given the handicap [4]. Our proposal of using specially crafted immersive systems is guided by the principle of focusing the user on the game tasks and not on the handicap. The use of head-mounted displays has the advantage of hiding any elements of the surrounding environment and the own body altogether. This may be considered as an important point as the patient will not be able to see his/her own affected limbs. But on another side to help in the establishment of new neural pathways the visuo-motor coordination plays an important role. This means that the executed movements should be somehow visible to enable the acquisition and integration of visual stimuli in sync with those movements [7]. This will reinforce the reintegration of sensory inputs affected by the stroke. As said by [3]: "there is no motor training that can be considered purely motor, as any type of motor stimulation implies, to varying degrees, integration of sensory information."

3.1 Embodiment and Visuo-Motor Coordination

In an attempt to address above described issues, our proposal consists in a virtual reality game where the user embodies an avatar. This approach is based on previous works that demonstrate that a user may experience embodiment of an avatar, and react to any aggression directed to the avatar as if it was towards his/her own body [9]. By seeing and controlling the avatar arms and hands as the own counterparts, the user will perceive this new body and hands approaching objects of the surrounding scenario. However, as stated above, the visuo-motor coordination implies that patient movements be mapped into the avatar movements, and this seems to be in contradiction with our intention of hiding his/her limitations. In fact it is necessary to leverage the visual perception of the own movements and to which extent the handicap is hidden.

To this end, our approach includes the mapping of the "possible" movements into the desirable movements. This mapping consists in the application of a scale factor applied to the limb motion with the addition of an offset value before applying it to animate the character correspondent limb. For that it is necessary to perform an initial calibration to obtain the associated parameters. Such calibration uses the initial movements are used to infer the range of possible movements that the user is able to perform and from this obtain both the scale factor and offset needed. As we may expect that the initial movements be more constrained than those performed enthusiastically after some period. Therefore, these parameters are verified and adapted during the execution to take into account any errors in the the initial estimates or some possible evolution on the range parameters.

3.2 Proposed Game

The proposed game includes a set of on a simple tasks, e.g. spheres appearing at a distant position on virtual space come towards the patient. In this case, the objective of the game is to catch green balls and dodge the red ones. The initial position of the spheres is random, and evolve along predefined paths towards the player. In the simplest case, the balls trajectories are on an horizontal plane for coping with the inability of the patient to raise his limb due to lack of muscular strength and control. In any situation for playing the game the patient must perform different movements whose required ranges and speed will be adjusted depending on the current difficulty level.

Whenever a green sphere is reached, the score increases, while catching a red sphere leads to a penalty that will decrease the accumulated score. This scoring system is at the centre of the motivation ingredients as beating the personal best record or some buddy's is one of the main motivational challenges presented to the player. Simultaneously the attained scores, as well as their evolution can serve a simple parameter to be analyzed by the therapist or physician. High scores can be related with high motivation, endurance and/or high recovery levels, while low scores typically indicate the opposite.

To give an example of another game under construction, there is an immersive version of the well known Tetris game, where the user must point at the falling shapes to move them and rotate them. By adjusting the game area to be big enough to occupy more or less of the user's view field, it is possible to customize it for each patient specific limitations and abilities.

3.3 Difficulty level management

Traditional computer games tend to exhibit a number of levels with increasing difficulty. This tends to motivate the player to repeat them with the aim getting more and more skills that will enable him/her to overcome each successive level. The typical use of these levels are either not adapted to players that may present limitations or difficulties as they may not be able to play after a (more or less) limited time, or becoming uninteresting to players in more advanced recovery stages [4].

In order to enable a patient to play for either a predefined amount of time, typically during a therapy session, or without time limits just for the pleasure of playing or following the motivation of achieving a faster recovery, a different management of game difficulty levels needs to be defined. On another side, varying the difficulty levels along the game play has positive influence in both the motivation and achieved therapeutic results. Nevertheless when the difficulty level is above the capabilities of the patient, he or she may get frustrated and loose interest. To avoid these undesirable effects a careful management of the difficulty levels must be put in action. Have said this, and to enable the use of the proposed game for different recovery stages, a few rules were defined:

- The difficulty level (L) of the game will increase along time and depends only on performance.
- If the player did not reach a given minimal score during some period of time, the difficulty level is reduced.
- The initial level suggested is based on the registered performance of the user during the most recent session.

These rules guarantee that the user does not loose the motivation either because the game just becomes too easy and thus boring, or too difficult and frustrating.

3.4 Visual field

In the design of this ball catching game a special attention was paid to the placement of the objects in the space, as to encourage the patient to explore his field of vision systematically from left to right to either touch or dodge the objects. This was addressed by adjusting the size of the volume where the balls depart from, and by the introduction of paths crossing from left to right (and right to left) vision fields. Vertically slanted paths are also available although typically less important for the rehabilitation processes.

For the Tetris-like game the same effect is achieved by making the game area big enough to make it large enough to cover most of the field of view of the user. This will force the user to scan the whole area from left to right in the search, or to control the movement of some of the falling shapes.

3.5 Reaction Time

Frequently, stroke survivors have a very poor response to external stimulus. A simple task, like catching an object thrown by someone, which under normal conditions would a simple and quick reaction, may become impossible or very difficult to be executed by a stroke affected patient. If fact the event and action recognition becomes slower, what contributes to an increase in the reaction time, or eventually loosing reaction capabilities at all.

Without loosing focus, some dynamic variations were introduced in the game in order to stimulate the patient reactions. These variations, besides reducing the monotony of the game, also have the purpose of improving the speed of limb movements over time. To achieve this the game includes:

- Variations in the speed of objects.
- Variations in frequency of objects generated in the initial volume.
- Variations in the direction of the objects' trajectories.
- Random inclusion of distracting factors, such as moving characters, or changing background pictures.

The objects speed will be changed to stimulate the patient react with more sudden movements to try to reach them. As the game goes on, and when the evolution of the scoring justifies it, small increments are made in the object speed, to make the task of reaching them slightly more complicated. The time between objects creation is also made shorter and the reaction time the patient has to comply with this to avoid loosing too many balls and thus improving the attained score.

In order to ease the task, at an early stage, only one object will be sent and a new one will be only generated when the previous one is reaches the person. This will comply with the initial difficulties of focusing in and tracking a single object at a time.

As the rehabilitation evolves in terms of amplitude of gestures, perception, vision field and reaction times, the frequency of object generation will increase progressively to having more and more moving towards the player. This will enable the patient to improve the concentration on the closest object until it is caught or lost. This represents not only an improvement at the visuo-motor level but also at the cognitive level.

4 Implementation

To validate the concept and evaluate usability and utility of the game an initial implementation was done, using the *Razer HYDRA controllers* and Oculus RIFT DK2 head mounted display (HMD).

The HMD is used to create the 3D immersion effect, causing patient to feel like he/she is part of the designed virtual world, and embodies the virtual model. In order for these desired effects to be achieved, patient's view is generated from the eyes perspective of the avatar. This enables that whenever patient looks around, he/she will feel like having full control of that model, as if he/she was dealing with his/her own body.

For the purpose of this game, the avatar control is limited to the orientation of the head and the affected arm. While the head pose is obtained directly from the Oculus Rift sensors, the arm is tracked using *Razer HYDRA controllers*, as shown in the figure 1.

Fig. 1: User playing the game.

4.1 Implementation Results

Figure 2a) shows the game start and the patient's initial score. It is expected that the player will start the *embodiment* process into the virtual model, as he/she starts to look around, as shown in figure 2b).

Whenever the patient is ready to start playing the game, he/she or therapist may press play in the game, and the launching of spheres towards the user will start. As previously described, the player must touch the green spheres as shown in figure 2c), and avoid the red ones (figure 2d)). As the game evolves, it automatically adapts in accordance to the patient performance, by either increasing or decreasing the difficulty level.

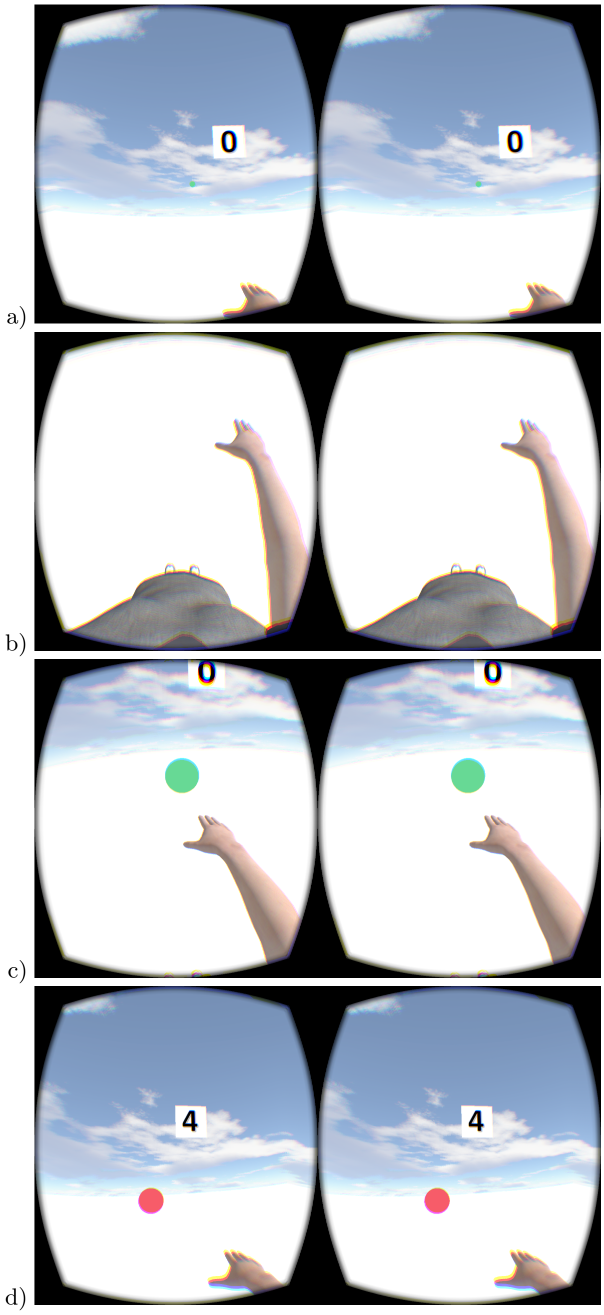

Fig. 2: a) Opening screen; b) Embodiment perception; c) and d) Green and Red spheres coming towards the player.

5 Evaluation

An initial study about the system's usability was made, that consisted of tests carried out with 8 users that have no impairments (volunteers from the undergraduates in the Department of Electrical and Computer Engineering at the University of Coimbra, with ages between 18 to 25 years old). These users had no relation or previous knowledge about this work, but have shown interest and were willing to perform tests and give feedback about it. Each user played the game twice and then replied to a questionnaire, that followed the System Usability Scale (SUS), according to [8].

Most of the participants (87.5%) answered positively the question if they had enjoyed the game, and 100% found the game easy to play. Moreover, they added that it met its purpose, being an useful aid for the current motor therapies and encouraging patients to perform more therapeutic exercises. On the other side, they claimed that using dynamic parameters bring a more meaningful experience to the game (e.g, speed of spheres, different scores depending on sphere's colour), as well as having the initial level of challenge either being set by therapists' advice or being based on the most recent session of a specific user. Figure 3 shows the plots that summarise the answers obtained to the 10 SUS questions, following the ones that are specified in [8] given via a *Likert* scale going from 1 (strongly disagree) to 5 (strongly agree).

More recently, a second evaluation was carried out at Caritas Diocesana de Coimbra with the presence of a specialist in physiotherapy, in order to assess the validity and usability of the game created. The feedback obtained from the therapist was very positive and validated the requirements discussed in the previous chapter, putting a special emphasis on requirements related to visual field stimulation, reaction time stimulation and increase in resistance. As the developed game relies on a simple virtual scenario, it causes the visual stimuli to be focused only on the moving objects, leading the patient to perform the proposed exercise without any distraction. From this a new validation is going to be conducted with real patients executing rehabilitation therapy.

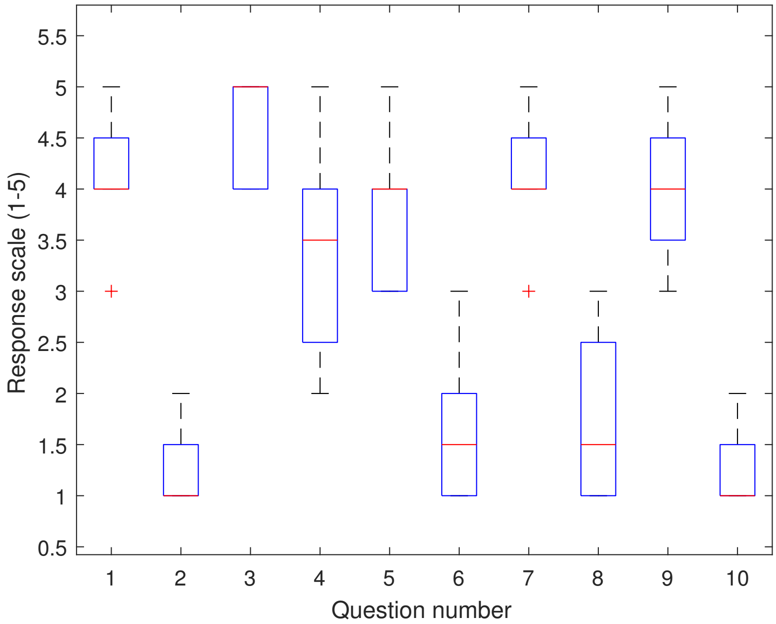

Fig. 3: System Usability Scale Results.

6 Conclusion

This paper presented the development of games for supporting the rehabilitation of motor skills in stroke survivors. Exploiting the potential of immersive systems in changing the perceived reality, a game is given as example of how the handicap may be moved away from the focus of attention of these patients and replaced by the game-related tasks which, although being enjoyable, have serious rehabilitation purposes. Two examples of games were presented and how they were tailored for the rehabilitation usage. The issues related to customization for each patient in particular and adaptability as the rehabilitation progresses were discussed. Finally a preliminary evaluation of one of the proposed games was performed with results confirming expected interest and validity.

7 Acknowledgment

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ments about post-stroke rehabilitation procedures that were integrated in the design of the presented game.

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Immersive Serious Games for Post-Stroke Motor Rehabilitation

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Abstract. This article describes a demonstration of an ongoing research work that explores the extents of how immersive systems may support serious games development for post-stroke upper limb rehabilitation. Beyond the entertainment that is expected from games, the focus goes towards the exploitation of embodiment that should contribute to reinforce the patient engagement, what is known to contribute to the faster and deeper recovery, but also the sensory stimulation that is crucial to the development of new neural pathways.

Keywords: Immersion · Sensory Stimulation · Virtual Reality· Engagement· Serious Games· Motor Rehabilitation· Stroke

1 Introduction

The use of Virtual Environments (VE) comprehending *serious games* for Motor Rehabilitation has grown into a significant area of interest given the number of possibilities that they can add to the well established therapies. Typically, impairments caused by stroke occur mainly on one side of the patient's body (*hemiparesis*), leading to corresponding upper limb to remain weak in up to 66% of the cases [3]. Motor rehabilitation therapies are usually intense and involve numerous repetitions of exercises considered important in order to help the patient to recover some lost day-to-day activities. Frequently the frustration by having lost some basic abilities leads to depressive states, that together with commonly slow recoveries lead to discouragement and loss of interest in the recommended therapeutic exercises. Moreover, patients frequently tend to try to forget the affected limb and try to learn to use the healthy one.

Literature shows that the enjoyment during the training encourages the patient to perform more and more repetitions [3,7,5] and, not surprisingly, leads to faster and better recovery. To this end, new technological devices have been introduced over time, such as Nintendo WiiMote, Sony Playstation Move or the Microsoft Kinect, to explore the execution of the necessary therapeutic gestures through video games. However common console games require the ability to use game controllers or to perform gestures or limb movements typically beyond what is possible for a stroke survivor. In fact, although these systems may lend the user the possibility to explore direct manipulation to play, the required direct mapping of gestures into game controls may result in frustration and abandon especially in the early stages, as the patients tend to not get any reward given their limitations. Virtual Reality (VR) may take this a step further as the games can be designed so the user experience becomes centred on the game itself, instead of his/her limitations.

2 Exploiting The Use of Immersive Systems in Therapies

VR-based games and head-mounted displays (HMD) are becoming more accessible and increasingly popular these days. They may be used to support experiences eventually enhanced other stimuli sources, making the user feel like he/she is in a different environment than the real one. This possibility of taking the user into "new realities" expands the frontiers of motor rehabilitation both by creating new and motivating situations to execute the necessary exercises. In fact, by wearing some HMD the user will not see his/her own body and therefore the affected body parts. This creates the perfect opportunity to map the possible upper limb movements into the required controls or to animate some movements of an avatar in the VE that may be seen as a "better/healthy version of oneself" leading to increasing the focus on the game and by choosing the appropriate controls to use them to improve the recovery as the patient tends to increase the playing time.

In fact these systems do not replace the conventional rehabilitation therapies, instead they bring new ways to perform them in the presence of the therapist. Besides, the gamification opens the possibility of extending their execution by the patients at home, given the entertainment they provide. As result one can expect that they contribute to: better patient engagement, increase in the number of exercises performed beyond the therapy sessions, with the consequent enhanced motor (re)learning. In addition this also opens the possibility for the therapists to have their patients' performance monitored and saved for later evaluation, both during formal therapeutic sessions and domestic use[6,4].

2.1 Sensory Stimulation on Post-Stroke Motor Rehabilitation

Although motor rehabilitation is frequently associated with muscle training to restore its tone and improving the accuracy of movements, sensory inputs play an important role in these therapies. In fact, when motor cortex is injured by a traumatic incident, such as stroke, the brain attempts to maintain control of motor coordination by remapping its sensorimotor interactions. Thus, any type of motor stimulation implies the integration of sensory information [2]. Using made-up sensory stimulation it is possible to have the user feel and acknowledge that a certain task is being performed, without actually accomplishing it totally by himself. This can be achieved through embodiment of some virtual character performing some task in spite of not being able to perform the same movements by oneself. Nevertheless by mapping the limited movements of the affected limb into the intended avatar movements, the user/patient may have the feeling of accomplishment. Conversely if the handicap comes from the deterioration of the proprioceptive neural pathway of the affected limb, the introduction of alternative stimuli such as sound, haptics on another body part, or visual during some game play, will enable the person to learn to perform and enjoy the exercises, contributing to the rehabilitation process. In fact, [1] hypothesizes that mirror neurons (considered to be visuomotor cells) can be linked to motor learning, as these cells activate when some oriented-object action is performed in front of the patient, leading the brain to consolidate its sensorimotor representation. This clearly lead us to believe that VR-based games that provide adequate sensory stimulation to its user are fundamental for the aid of the motor rehabilitation therapies.

2.2 Developing Serious Games for Motor Rehabilitation

Our specifically crafted game consists on a three dimensional representation of a Tetris Game, meaning that it will both stimulate the motor and cognitive activities. The VE containing the game was developed considering the following properties: the user's point of view of the virtual scenario, the available space to perform the desired tasks, as well as the objects and its placement within the virtual space.

The user will have to guide the falling pieces with his/her affected limb into the desired and most suitable position in the playing area. During their fall, they might need to be rotated, which can be performed by two different actions depending on the recovery stage of the user/patient: a rotation of the player's hand (similar to rotating a door's knob) or by pressing a button existing on the controller. A scoring mechanism will be responsible for tracking the user's performance, while constantly adapting and gradually increasing or decreasing the level of challenge. In order to allow the use of the game on different recovery stages, a number of rules were defined, such as: 1) The level of challenge may be changed by: Changing the generation rate of the pieces and/or increasing or decreasing their falling speed. 2) The initial level of challenge is suggested either based on the therapist's initial configuration or by the most recent registered performance.

2.3 Experimental Apparatus

The setup needed for this experiment requires four devices: a laptop, an Oculus RIFT, a Razer Hydra and a regular pair of headphones. The Razer Hydra allows us to estimate the position and orientation of the user's hand. The use of these devices allow the system to be easily moved around and uses little space. The figure 1 shows an example of an user playing the game while sitting.

3 Conclusion

In this paper we presented a proposal of using an immersive system for the aid of the conventional motor rehabilitation therapies by

Fig. 1: User playing the game.

stimulating their sensory inputs in order to become part of a made-up reality. For attaining this purpose, a VR-based game is used with the aim to lead the patients to execute the therapeutic exercises while focusing on the game itself and not on their limitations.

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