StableHand VR: a Virtual Reality serious game for hand rehabilitation

Margarida Inês Fernandes Pereira

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Universidade do Minho
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Dissertation oriented by
**José Manuel Ferreira Machado**
**Nuno Feixa Rodrigues**

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“ It's the questions we can't answer that teach us the most. They teach us how to think. If you give a man an answer, all he gains is a little fact. But give him a question and he'll look for his own answers. ”

Patrick Rothfuss (2011). “The Wise Man's Fear”

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To my loving parents and family, for the unconditional love and support. For allowing me to follow my goals and always encouraging me to go further. For being my rock.

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# STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

# ABSTRACT

A third of all injuries at work are sustained to the hand, and hand and wrist injuries are estimated to account between 10% to 30% of all Emergency Department (ED) attendances. In 2017, there were approximately 18 million hand and wrist fractures, 2 million thumb amputations and 4 million non-thumb digit amputations worldwide.

Several injuries, disabilities and diseases can affect manual motor control. Hand physiotherapy is indispensable to restore hand functionality. However, this process is often a strenuous and cognitively demanding experience.

This work proposes a Virtual Reality (VR) serious game to improve conventional physiotherapy in hand rehabilitation. It focuses on resolving recurring limitations reported in most technological solutions to the problem, namely the limited diversity support of movements and exercises, complicated calibrations, and exclusion of patients with open wounds or other disfigurements of the hand.

Concepts such as mixed reality, serious games for health, and hand rehabilitation are addressed in this dissertation to provide the reader with a background for the project. The latest developments of digital games and technologies in the hand rehabilitation field, specifications, requirements, general game characteristics and the most relevant details of the game implementation process are also presented in this dissertation.

The system was assessed in two mid-term validations to test its viability and adjust the development. The first validation was performed with eight able-bodied participants and the second with four health professionals working in the rehabilitation field. The validations were performed following ten minutes of guided functional task practices followed by a Semi-Structured Interview for the first validation and an online questionnaire for the second validation. The questions made in the interview and online questionnaire focused on the participants' familiarity with videogames, opinion about the Oculus Quest and its hand tracking system, and the StableHand VR game.

The System Usability Scale (SUS) scores obtained and the participants' positive feedback showed the potential of both conceptual and technological approaches adopted for this game as a viable complement to conventional hand rehabilitation. The project's main objectives were achieved, and several relevant topics for further research were identified.

**Keywords**: StableHand VR, videogames, hand rehabilitation, Virtual Reality, Oculus Quest, serious games.

# RESUMO

Um terço de todos os ferimentos no trabalho afetam a mão e estima-se que 10% a 30% de todos os atendimentos nas Urgências se devem a ferimentos na mão e no pulso. Em 2017, houve aproximadamente 18 milhões de fraturas da mão e do pulso, 2 milhões de amputações do polegar e 4 milhões de amputações de dígitos não polegares em todo o mundo.

Vários ferimentos, deficiências e doenças podem afetar o controlo motor manual. A fisioterapia é indispensável para recuperar a funcionalidade da mão. No entanto, este processo é frequentemente uma experiência extenuante e cognitivamente exigente.

Este trabalho propõe um jogo sério em Realidade Virtual para melhorar a fisioterapia convencional na reabilitação da mão. O trabalho desenvolvido concentra-se na resolução de recorrentes limitações relatadas na maioria das soluções tecnológicas para o problema, nomeadamente o apoio limitado de diversidade de movimentos e exercícios, calibrações complicadas e exclusão de pacientes com feridas abertas ou outras desfigurações da mão.

Esta dissertação aborda conceitos como a realidade mista, jogos sérios para a saúde e reabilitação para fornecer ao leitor contextualização para o projeto. Os últimos desenvolvimentos de jogos digitais e tecnologias no campo da reabilitação da mão são também apresentados nesta dissertação, assim como especificações, requisitos, características gerais do jogo e o processo de implementação do mesmo.

O sistema foi avaliado através de dois ensaios realizados durante o processo de desenvolvimento, para testar a viabilidade e proceder a ajustes da solução especificada. A primeira validação foi conduzida com oito participantes saudáveis e a segunda validação com quatro profissionais de saúde que trabalham em reabilitação. As validações foram realizadas após dez minutos de práticas funcionais orientadas, seguidas de uma Entrevista Semiestruturada, no caso da primeira validação, ou de um questionário online, no caso da segunda validação. As perguntas feitas na entrevista e no questionário online centraram-se na familiaridade dos participantes com os videojogos, opinião sobre o Oculus Quest e o seu sistema de localização de mãos e o jogo StableHand VR.

As pontuações obtidas no *System Usability Scale* e o feedback positivo dos participantes demostrou o potencial das abordagens conceptuais e tecnológicas adotadas para que este jogo fosse visto como um complemento viável para a reabilitação convencional das mãos. Os principais objetivos do projeto foram alcançados, tendo também sido identificado um conjunto de tópicos relevantes de investigação futura.

**Palavras-chave**: StableHand VR, videojogos, reabilitação da mão, Realidade Virtual, Oculus Quest, jogos sérios.

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# List of Abbreviations and Acronyms

## A

**AR** Augmented Reality

**AV** Augmented Virtuality

## E

**ED** Emergency Department

## H

**HMD** Head-Mounted Display

## I

**ICD-10** International Classification of Diseases 10th revision

## L

**LMC** Leap Motion Controller

## S

**SDI** Socio-demographic Index

**SUS** System Usability Scale

## V

**VR** Virtual Reality

# Glossary

**Augmented Reality (AR)** In AR, computer-generated graphics are superimposed on a user's view of the real world, providing him more information about the objects he is seeing. AR is usually offered through specific purpose glasses, or devices with a screen and a camera, such as tablets or smartphones.

**Augmented Virtuality (AV)** Augmented Virtuality can be achieved through entirely graphic display environments, either completely immersive, partially immersive, or a setting to which some video or texture reality has been added. AV implies that real objects, even the gamers themselves, can be projected into and participate in a virtual world.

**Direct Interaction Method** In the direct interaction method, the player's hands interact with the components by, for instance, reaching a finger out to "poke" at a button or reaching out a hand to "grasp" an object by pinching it.

**Far-Field Components** Far-field components are components that are beyond arm's reach. The player needs to use a raycast or locomote closer to the element to bring it into the near-field to interact with them.

**Gamification** Gamification applies typical game-design elements of game principles to other activity areas in non-game contexts.

**Near-Field Components** Components that are within arm's reach and use a direct interaction method.

**Raycasting Interaction Method** Raycasting is an interactive tool used in immersive environments to select targets for both near- and far-field components. This method resembles real-life pointing with a laser pointer were the user points a ray of light at the object or target and confirms its selection with a button click, a motion gesture, or a voice command.

**Reality-Virtuality Continuum** The Reality-Virtuality Continuum is a continuous scale that provides a classification of all possible variations between an utterly virtual environment and a completely real environment.

**SDK** SDK is the acronym for Software Development Kit. This development kit brings together a group of tools that help the programming of applications.

**Serious Games** Games that do not have entertainment, enjoyment, or fun as their primary purpose but for learning and training

**Virtual Reality (VR)** VR immerses the observer into a completely simulated virtual world and can be delivered by Head-Mounted Displays, Powerwall screens, or Cave Automatic Virtual Environments.

# 1 INTRODUCTION

## 1.1 CONTEXT AND MOTIVATION

The hand can be viewed as an extension of the brain. It reflects our mind, allows communication with people, and interaction with everyday objects and tools [1]. The hands' constant use comes with an increased risk of wounds, injuries, and trauma. A third of all injuries at work are sustained to the hand [2]. Hand and wrist injuries are estimated to account between 10% to 30% of all Emergency Department (ED) attendances [3].

Hand trauma global incidence has only modestly decreased since 1990. In 2017, approximately 18 million hand and wrist fractures were accounted, along with 2 million thumb amputations and 4 million non-thumb digit amputations worldwide [4].

Even though hand trauma is common and affects all demographic groups, the rate of injury varies greatly by region with improvements not being equally distributed. Socio-demographic Index (SDI) countries currently report the highest-burden of hand trauma. However, middle and low-middle SDI countries have increased hand trauma rates by 25% over the last 27 years [4].

In 2017, the highest overall number of hand and wrist fractures was observed in South and East Asia; however, Central Europe, Australasia and Eastern Europe observed this injury's highest age-standardised rate. Within these regions, New Zealand, Czech Republic Slovenia, Slovakia, Poland, and Australia presented the highest age-standardised hand and wrist fractures rates. Southeast Asia and Tropical and Central Latin America presented a lower incidence, and overall, the lowest incidence was noticed in Timor-Leste, Laos, Mauritius, Indonesia, and the Philippines [4].

High-income North America and Western and Eastern Europe reported the highest overall digit amputations. In Oceania, Andean Latin America and the Caribbean, the incidence of digit amputations (thumb and non-thumb) was the lowest. The highest incidence of thumb amputation was observed in Australasia, followed by Central and Eastern Europe. Timor-Leste, Laos, Philippines and Mauritius had the lowest thumb amputation incidence. Non-thumb digit amputation was observed in highest incidence in Australasia, followed by Eastern and Central Europe, while Indonesia, Timor-Leste, Laos and Mauritius had the lowest incidence [4].

East Asia reported the most significant increase in injury incidence by region since 1990. This region noted a 63%, 47%, and 57% increase in the age-standardised fracture, thumb amputation, and non-thumb digit amputation rate. The majority of these increases occurs in

China and North Korea. Regions such as Oceania, Caribbean, Tropical and Southern Latin America also increased injury's rates, but not to the same magnitude as East Asia. Sub-Saharan Africa and the Middle East presented variable patterns of change. However, a substantial reduction in fracture, thumb amputation rates, and non-thumb digit amputation was experienced North America [4].

Young, male, working population comprise the majority of those who sustain hand and wrist fractures, with most injuries sustained either at work or during sport. However, males have experienced a greater reduction in these injuries since 1990 compared with females [4], [5].

An analysis of Hospital Episode Statistics in England from 1998-1999 to 2014-2015 showed that hand injuries' overall incidence increased from 70 to 110 per 100 000 individuals. In the 17-year period studied, 845 890 episodes of hand injuries were recorded with the possible following diagnoses: hand fractures, tendon injuries, nerve injuries, blood vessel injuries, traumatic amputations and nail bed injuries [5].

From the hand diagnosis analysed, hand fractures were the most common recorded hand injury, accounting for 49% of injuries in 1998-1999 and 53% in 2014-2015. Hand and wrist fractures were recorded as the fastest-growing injury, increasing steadily from 34 to 60 fractures per 100 000 individuals. Especially large incidence increases were encountered in fractures in the over 75 years age group. Analysis of fracture type in 2014-2015 revealed the most common injuries were to the fingers (46%) and the metacarpals (36%). Finger fractures were the most common fractures in all age groups [5].

The 15–59 years age group presented the highest rate of injuries to hand's tendon and muscle, with an occurrence of 29 per 100,000 in 2014–2015. Few blood vessel injuries were recorded as the primary diagnosis, with <1 per 100,000 individuals in all age groups. Nerve injuries incidence presented a slight increase in all age groups except paediatric cases. The total number of nerve injuries increased from 3400 in 1998–1999 to 4790 in 2014–2015. The majority of digital nerve injuries occurred in the finger (55%) and thumb (14%).

Regarding nail bed injuries, these are increasingly common, especially in the 0–14 years age group, while traumatic amputation at the wrist level was uncommon, occurring 1–12 times per year in the whole of England. Over the study period, the fingers and thumb's absolute number of traumatic amputations increased slowly. However, these injuries' occurrence was low and did not change significantly in this time. Among traumatic amputations, partial or complete amputation of the finger was the most common injury and occurred 2562 times in 1998–1999 and 3495 times in 2014–2015 [5].

Hand and wrist injuries can affect both social and professional activities. These injuries are incredibly common, affecting all ages, sexes and geographic regions [4].

Recovering full hand function is a strenuous and cognitively demanding process. Aftercare typically takes the form of physiotherapy sessions, conducted in professional health care facilities. These conventional therapies' economic burden comprises direct (medical expenses incurred), indirect (value of lost productivity) and intangible costs. The main cost factor resides in the scalability, i.e., in the occupation of the required facilities and the full-time intervention of healthcare professionals in sessions, limiting the number of patients treated at any given time.

Robinson et al. [6] searched 764 studies to provide economical cost estimates of hand and wrist injuries burden and discuss the cost components used in international literature. Twenty-one studies met the inclusion criteria: twelve were cost-of-illness studies, and seven were health economic evaluations. Indirect costs constituted a large portion of total cost in all studies, with a percentage of 64.5% in cost-of-illness studies and 68% in health economic evaluations. Cost-of-illness studies presented a median total cost per case of US$6 951 and health economic evaluations a cost of US$8 297. Few studies stated intangible costs associated with acute hand and wrist injuries.

Robinson and Brien [3] analysed data from two EDs across two financial year periods (2014-2015 and 2015-2016). In the 2-year study period, the total cost of ED direct and indirect medical costs was AU$1 923 852.38 in 2014–2015 and AU$2 035 683.00 in 2015–2016. Per presentation, there was a mean cost of AU$383 in 2014–2015 and AU$407 in 2015–2016.

Fractures of the wrist and hand were the second most frequent International Classification of Diseases 10th revision (ICD-10) category with 2895 incidences (28.9%). These injuries accounted for the highest total costs' proportion (38.3%; AU$1 514 967.33), with a mean cost per ED episode of care of AU$489 in 2014–2015 and AU$558 in 2015–2016 [3].

Open wounds of the wrist and hand, with 3448 incidences, accounted for 34.4% of total costs (AU$1 170 964.38) with a mean cost per episode of AU$331 in 2014–2015 and AU$347 in 2015–2016. When considering mechanism of injury, fall or fall on outstretched hand accounted for the highest costs (AU$1 025 588.58) followed by lacerations (AU$985 339.50), and sports injuries (AU$562 849.42), over the 2-year period [3].

Scalable solutions that reduce the costs associated with the rehabilitation process, increase patient motivation, decrease physiotherapy session duration, or allow sessions to be held outside professional facilities will substantially impact hand rehabilitation therapy's increased availability. These solutions should be created according to human ethical parameters and provide useful recommendations for the users [7], [8].

Several technologies have been proposed to help patients to conduct rehabilitation at home. Without any technical support, home sessions must be easily understood and performed by patients, which often leads to the implementation of simple sets of repetitive exercises. For such interventions, the patient's motivation to perform the activities is of utmost importance. Long term rehabilitation might not be achieved due to a lack of patients' adherence. However, there is strong evidence that these limitations can be mitigated by a more entertaining, engaging, and enjoyable form of delivering therapy exercises.

Gamification, defined as "the use of game design elements in non-game contexts" [9], is a promising technique that has been successfully used to drive motivation in different contexts. One of the most popular implementations of gamification processes is accomplished through video games, which have been designed for various pathologies and medical conditions and have the potential to provide readily available and affordable rehabilitation exercises.

In more recent years, Augmented Reality (AR) and Virtual Reality (VR) training systems combined with desktop computers and smartphone apps have been used for rehabilitation as a supportive addition to conventional therapy. These technologies provide new opportunities to increase the immersion feeling in interactive applications. Combined with other game development techniques, they can increase user engagement, ultimately resulting in an improved overall experience [10], [11].

Pereira et al. [12] reviewed the effectiveness of AR and VR interventions for hand rehabilitation, showing that in most cases advanced technology offers similar results to conventional therapy, even though they do not provide a complete substitute to the health professional. Six of the eight selected works showed improvements in the intervention group, and the other two no statistical differences between groups. These systems can enrich treatment by motivating the patient's adherence, providing real-time feedback, challenge, and increasing individualised difficulty. Automated tracking, easy integration in the home setting, and accurate metrics recording may improve the scalability and facilitate healthcare professionals' assessments.

In early 2020, Oculus launched a Hand Tracking SDK for their Oculus Quest headset. A new method that uses deep learning was developed to understand the players' fingers position resorting only to Quest's monochrome cameras. This technology approximates the shape of the players' hands. It creates a set of 3D points to accurately represent the hand and finger movements in VR, bringing several advantages to the VR world for hand rehabilitation. Oculus Quest does not require additional hardware and has an inside-out tracking, eliminating the need for a cable connection.

This work was developed in close contact with researchers and physiotherapists from the Department of Plastic and Reconstructive Surgery of the BG Trauma Clinic Tuebingen. This dissertation presents a VR game's conceptualisation and implementation to complement conventional hand physiotherapy sessions.

## 1.2 MAIN AIMS

This work's principal motivation is to develop an engaging application for patients suffering from diverse hand disabilities or injuries. The main goal is to improve patients' adhesion and results during physiotherapy sessions by providing an attractive rehabilitation tool. This application can be achieved by combining leisure and clinical rehabilitation through an influential tool currently being broadly used: serious games.

Several disabilities can affect the hand and its motor control ability, resulting from nerve or soft tissue damage or traumatic amputation. Regaining the hand's full function is a strenuous and cognitively demanding process, usually accompanied by pain. A solution that immerses the patient in the rehabilitation would provide a sense of pain abstraction and possibly, better outcomes. Therefore, the solution presented will resort to a VR Head Mounted Display and an interactive 3D game.

Gamification through VR in hand rehabilitation can improve muscle tonus development and increase gestures precision. The hand movements' kinetic data will be recorded within the VR application. By using VR, it is also possible to capture parameters that otherwise cannot be inspected. For example, the patients' time to complete the standardised tasks. It is expected that this will enable identifying additional therapy parameters that will make it possible to objectively measure not only purely motor aspects of hand movement but also rehabilitation success.

This work aims not to substitute the physiotherapist, but to provide autonomy to the patient, reduce the amount of supervised time in each session, and extend quality physiotherapy beyond health care units.

The application proposed in this thesis presents itself as a complement to the occupational/traditional therapy health professionals use. As a result, it is an effort to engage and motivate patients in the routine tasks they are asked to perform during rehabilitation sessions.

## 1.3 INVESTIGATION METHODOLOGY

Before writing this dissertation and the project's initialisation, a detailed investigation was performed. The analysis addressed the viability of the project (i.e. the VR game for hand rehabilitation), searched the best software to deliver the game, searched the preferred test groups and discovered which pathologies were treated with similar games. The Design Science Research (DSR) strategy was followed to assist in this process. The DSR methodology presented in Figure 1-1 is a rigorous scientific research methodology considered very useful in the computer science field [13], [14].

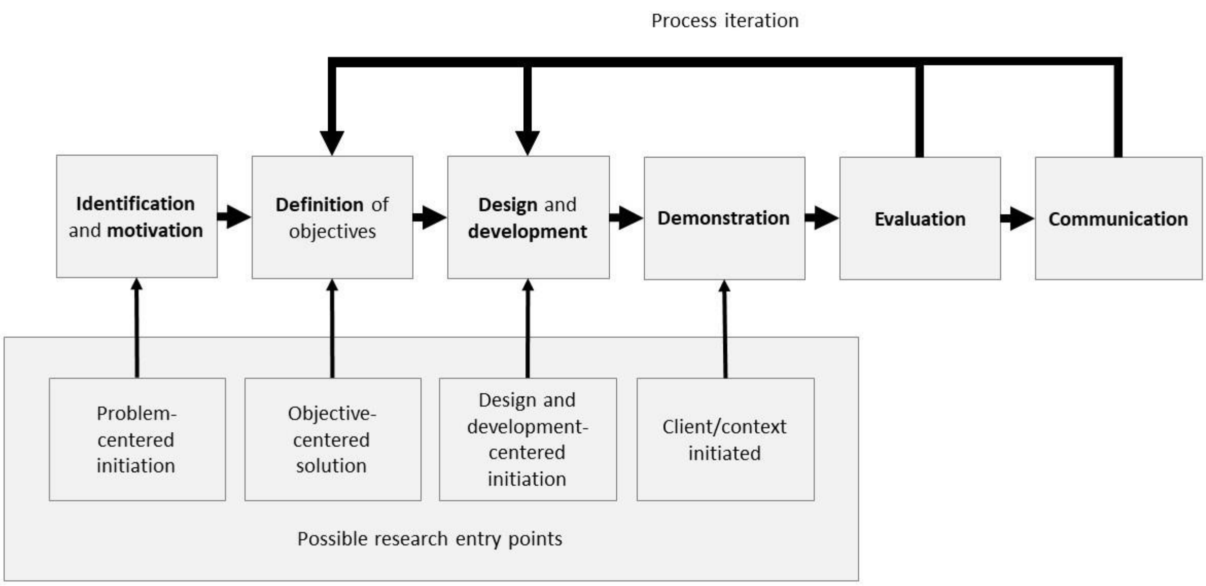



Figure 1-1. Design Science Research methodology (adapted) [14].

DSR process generally includes six phases:

(1) **Identification** of the problem and **motivation**

Literature research in the form of a Systematic Review was performed to identify and define the research problem and justify a solution's value. A systematic review is a form of analysis and assessment of a clearly stated question that uses "systematic and explicit methods to identify, select and critically appraise relevant research, and collect and analyse data from the studies that are included in the review" [15].

In some cases, systematic reviews are used by Agencies and Clinicians as a way to justify further research on the proposed investigation topic [15]. This method of finding and selecting studies to analyse is more likely to reduce bias and produce reliable and accurate conclusions.

The main question addressed in the systematic review was: "What is the effectiveness of AR/VR applications in rehabilitating patients with hand impairment compared to a conventional intervention?". This question was complemented with six research questions concerning three main topics of interest to analyse in the selected studies: the targeted patients, the technology and equipment itself, and the study's outcomes [12].

(2) **Definition of objectives** for the solution

After the initial research in the form of a Systematic Review and obtaining confirmation that it was a justifiable project for further investigation, objectives to be attained for the solution were defined. The objectives consisted of: defining project requirements, researching possible software and devices to use (with advantages and disadvantages) and researching the necessary gestures for hand physiotherapy that should be implemented in the game.

(3) **Design and development** of the solution

The Design and development phase includes the features and designs of the solution and the respective product development to solve the problem identified. This was accomplished through the planification of the game mechanics and architecture; main design of the scenarios; Unity integration with Oculus Quest SDK; hand tracking integration; database integration; multi-language menu implementation; and tutorial scene creation.

(4) **Demonstration** of the solution

The demonstration phase included all the experiments and simulations involved in testing and demonstrating the solution, leading to the final game version. This demonstration was performed in the form of guided functional task practice.

(5) **Evaluation** of the solution

The solution's evaluation intends to compare the solution's objectives and the actual observed results. Two validations of the solution were performed: the first on able-bodied participants and the second on able-bodied health professionals. The first and second validations consisted of ten minutes guided functional task practice followed by a Semi-Structured Interview/online questionnaire, respectively. The validations content was evaluated, focusing on a detailed analysis of the participants' answers.

(6) **Communication** of the solution

The solution's communication and its utility and effectiveness to other researchers and practising professionals was performed through this dissertation and a conference paper [16].

## 1.4 STRUCTURE OF THE DISSERTATION

This dissertation is structured in 8 sections. The first section is the i. The Background is the second section and describes essential concepts that the reader should know to understand the problem. State of the Art presents the latest developments of digital games and technologies in the hand rehabilitation field. The section Specifications describes the problem, requirements and general game characteristics to be achieved in the Implementation section. This section describes the materials and methods used for solving the main issue presented in the first sections. Two validations of the solution were performed and are shown in the Results section. Subsequently, in the Discussion section, the obtained results are discussed and evaluated. Finally, the last section of this dissertation is the Conclusions where the problem, the obtained solution, and the results from its validation are summarised and discussed. Prospects for future work are also presented in this last section.

## 1.5 CONTRIBUTIONS

M. F. Pereira, C. Prahm, J. Kolbenschlag, E. Oliveira and N. F. Rodrigues, "A Virtual Reality Serious Game for Hand Rehabilitation Therapy," 2020 IEEE 8th International Conference on Serious Games and Applications for Health (SeGAH), Vancouver, BC, Canada, 2020, pp. 1-7, doi: 10.1109/SeGAH49190.2020.9201789.

M. F. Pereira, C. Prahm, J. Kolbenschlag, E. Oliveira, and N. F. Rodrigues, “Application of AR and VR in hand rehabilitation: A systematic review,” J. Biomed. Inform., vol. 111, p. 103584, 2020, doi: https://doi.org/10.1016/j.jbi.2020.103584.

# 2 BACKGROUND

## 2.1 MIXED REALITY

In recent years, both AR and VR terms have frequently appeared in the literature. The Reality-Virtuality Continuum, as presented in Figure 2-1 provides a classification scale of all possible variations between an utterly virtual environment and a completely real environment. The area between the two ends is called mixed reality and is where both Reality and Virtuality are mixed under different conditions [17].

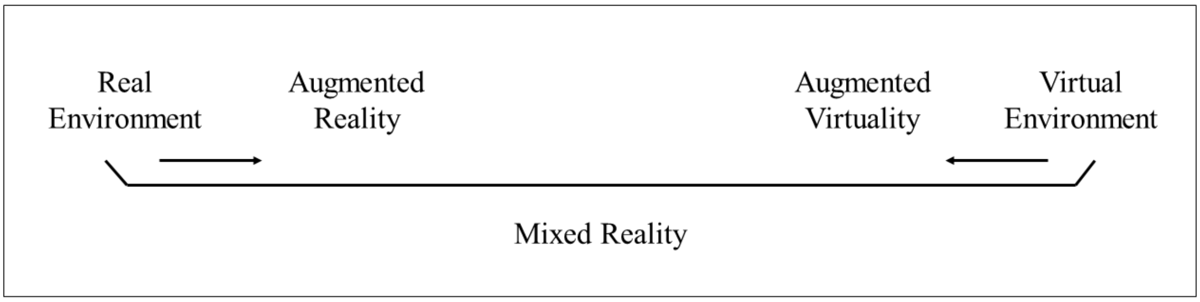



Figure 2-1. Simplified Reality-Virtuality Continuum (adapted) [17].

In the Reality-Virtuality Continuum, two concepts could be viewed as antitheses: the Real Environment and the Virtual Environment, but it is more appropriate to see them as opposite ends of a continuum. A strictly real environment must be constrained by physics laws, while in a virtual environment, these laws can be forgotten entirely [17].

In AR, computer-generated graphics are superimposed on a user's view of the real world, providing him more information about the objects he is seeing. AR is usually offered through specific purpose glasses, called smartglasses (e.g. Microsoft HoloLens, Epson MOVERIO), or any device with a screen and a camera, like a tablet or a smartphone [18].

Augmented Virtuality (AV) can be achieved through entirely graphic display environments, either completely immersive, partially immersive or a setting to which some video or texture reality has been added [17].

VR or Virtual Environments immerses the observer into a completely simulated virtual world and can be delivered by Head-Mounted Displays, Powerwall screens, or Cave Automatic Virtual Environments. More generally, VR can be defined as any computer-based device that provides visual stimuli on a monitor or wall screen display, like video games. These can be considered as less immersive virtual environments when compared to Head-Mounted Displays (HMD) [11], [18], [19].

The factors distinguishing Real Environment, Augmented Reality, Augmented Virtuality and Virtual Environment concepts go well beyond systems configuration such as see-through (ST), monitor-based, or head-mounted displays. The definition of these systems needs to dwell on the expected feeling the user will have, i.e. if the user feels egocentrically immersed within the world or exocentrically looking into that world. There are even other issues, such as how much one knows the world and how the interaction can happen [17].

To answer the concepts convergence issue in the Reality-Virtuality Continuum, Milgram et al. [17] created a set of questions to better "distinguish essential differences and similarities between the various display concepts" in Mixed Reality. These questions are summarised in Table 2-1.

The first column of the table presents the significant distinction separating the real environment from the virtual environment, i.e., whether the substratum defining the principal scene derives from a Real World or a Computer Generated world [17].

The distinction about the hardware used to display the scene is made in the second column, where a Direct view is created when the principal world is view directly, through air or glass. A Scanned substrate view is the opposite where the world must be scanned by some means, such as video cameras, and then reconstructed by some medium such as video or computer monitors [17].

The third column addresses the viewer's perspective, distinguishing egocentric and exocentric references. An egocentric reference is a first-person "self-based" reference, i.e. it is a frame of reference in which objects are represented relative to the perceiver. An exocentric reference consists of a third person "world-based" reference, i.e. it is a frame of reference in which objects are represented relative to the environment that is extrinsic to the perceiver.

In mathematics, conformal mapping is an angle preserving function that allows for a shape-preserving distortion that can map a field of view to an arbitrary display configuration. This function that locally preserves angles, orientation, and direction, does not necessarily maintain lengths. The question of whether a strict conformal mapping is necessary is addressed in the fourth column.

Table 2-1. Differences and Similarities between the Classes of Mixed Reality displays (adapted) [17]

| Class of Mixed Reality system | Questions | | | |
|---|---|---|---|---|
| | (R) or (CG) world | (D) or (S) view of substrate | (EX) or (EG) reference | (1:1) or (1:k) |
| 1. M-based video, with CG overlays | R | S | EX | 1:k |
| 2. HMD-based video, with CG overlays | R | S | EG | 1:k |
| 3. HMD-based optical ST, with CG overlays | R | D | EG | 1:1 |
| 4. HMD-based video ST, with CG overlays | R | S | EG | 1:1 |
| 5. M/CG-world, with video overlays | CG | S | EX | 1:k |
| 6. HMD/CG-world, with video overlays | CG | S | EG | 1:k |
| 7. CG-based world, with real object intervention | CG | D, S | EG | 1:1 |

R: Real; CG: Computer Generated; D: Direct; S: Scanned; EX: Exocentric; EG: Egocentric; 1:1: Conformal Mapping; 1:k: not Conformal Mapping; M: Monitor; HMD: Head Mounted Display; ST: See-through.

The StableHand VR game described in this dissertation is an entirely virtual environment which falls under category number 6. HMD/CG-world, with video overlays Class of Mixed Reality system.

## 2.2 SERIOUS GAMES FOR HEALTH

The first formal definition of a serious game appears to have emerged in the book "Serious Games", by Clark C. Abt (1970). The author presents simulations and games to improve education through mainframe computer or pen-and-paper based games since the video game industry was not yet established. Throughout the years, the concept of serious games has changed. In 2002, Sawyer provided an updated definition of Serious Games based on the idea of connecting a serious purpose to knowledge and technologies. The definition describes serious games as the use of "digital game entertainment techniques for non-entertainment purposes" [20].

Based on Sawyer's definition, other definitions of serious games were created. Even though there is no single definition of the concept at present, most researchers agree that serious games are games that have learning and training as their primary purpose, and not entertainment, enjoyment, or fun [21].

During recent years, an increasing number of serious games have been developed for a wide range of fields, such as healthcare [22]–[24], education [25]–[27], emergency preparedness [28]–[31], social interaction [32], [33] and environment [34], [35].

The use of interactive systems for health involves many benefits to the professional area of medical training, for example, for surgery training [36], to patients' private use in rehabilitation [37], nutrition [38], exercise [39], and promoting a healthier lifestyle [40].

Games for health can help patients achieve behavioural change, learn new skills, and exercise independently. They can also reduce the practitioner's workload, allowing remote monitoring of patients' progress. By educating physicians, physiotherapists, and patients about serious games for health, a lot of different solutions can be developed and tested to improve patients' treatments and lifestyle.

The advantages of serious games go well beyond capturing the player's attention and sustaining that attention. Games can be designed to provide task-oriented exercises and be tailored to individual ability levels. Games are not limited by what is plausible in the real world but can simulate just about any phenomenon that the designer might want players to understand. Games provide a prospect for inductive and deductive reasoning in real-time, visual and auditory feedback regarding performance and gain, engaging players to increase the rehabilitation intensity, being easily integrated into the home setting, and can motivate individual learning. A well-designed game involves players in the game experience by slowly increasing cognitive challenges as the player's skill level rises [12], [41].

Features of optimal learning comprise the following four pillars, which should be carefully implemented in serious games [42]:

- Paying **attention** to the tasks being made;
- **Active learning** engages players in the process of learning through activities and has been shown to be more effective than traditional education;
- **Feedback** with task focus has positive effects on performance and motivation;
- **Memory consolidation** can be easily achieved through concentration and repeated training. Learners learn more when multiple training sessions are involved.

In the field of serious games, this work will focus on games for health, particularly in games for health used in rehabilitation. The proposed game is designed to improve hand-related neuromuscular and motor function.

## 2.3 HAND REHABILITATION

The human hand is one of the most versatile and powerful evolution results, perhaps only surpassed by the human brain's importance. Our hands are the perfect tool at the service of our inventive brains, having played a fundamental role in the dominance of the human species since prehistoric times, and today as our main interface tool to control the most advanced technologies. It is crucial not only because of its social and psychological significance, but also because of its versatile functionality in communication, gestures, and sensation [6], [43].

It is no wonder then that in an increasingly technological world, the hand is constantly requested for a wide range of human tasks. This constant and intensive use comes with an increased risk of subjecting the hand to wounds, injuries, and trauma during a lifetime. Therefore, injuries sustained to the hand are very common, making up a third of all injuries at work [2], [6], [43].

Several injuries and disabilities as sequelae of injury or disease can affect the hand and its motor control. Some of the most common injuries in athletes and non-athletes are tendon lacerations, injuries, and transfers; contracture releases; ligament ruptures and injuries; fractures; fingertip Injuries; joint sprains and dislocations [44], [45]. Diseases such as stroke, juvenile idiopathic arthritis, cerebral palsy, brachial plexus birth injury, and multiple sclerosis were identified in the literature as reasons for impairment [12].

The overall cost and the burden of these injuries to the patient can be very extensive. Its economic effect goes well beyond hospitalisation cost, including high aftercare costs, lost productivity, and other intangible costs [6], [43].

Rehabilitation usually takes the form of therapy sessions. In these sessions, patients perform specific exercises for a fixed period, under the supervision of a health professional, typically a physiotherapist or an occupational therapist. The health professional oversees the selection and intensity of rehabilitation protocols for each patient.

General hand and wrist rehabilitation are performed in four phases: splinting, oedema control, range of motion, and strengthening [44].

In the first phase, the goal is to immobilise the hand in a safe position for injured tissues. By resting the tissues, a decrease in pain, and inflammation follows. Static splints are often applied as soon as the affected tissues heal and before the hand stiffens [44].

The second phase, oedema control, should also be initiated as early as possible. If not controlled, oedema can lead to contractures. Techniques such as splints, elevation, external compression, and active exercise decrease postinjury oedema. [44].

The third phase is the range of motion. An active range of motion benefits includes reduced oedema, increased joint nutrition, and muscle atrophy prevention. Active range of motion is started as soon as the injury stabilises and can endure the forces created by an active motion protocol. Health professionals often recommend a six-pack hand exercise program that ranges every joint of the hand fingers when properly performed. The six-pack hand exercise program includes the following exercises: (1) make a tabletop with fingers by keeping the wrists and the end and middle joints of the fingers straight and bending only at base joints (knuckles); (2) keep base joints (knuckles) and wrist straight; bend and straighten the end and middle joints of the fingers; (3) make a fist, being sure each joint is bending as much as possible; (4) straighten fingers as much as possible; (5) make an "O" by touching thumb to fingertips one at a time; Open hand wide after touching each finger; (6) rest hand on table with palm down, spread fingers wide apart and bring them together.

After the six-pack exercise, joint blocking techniques are used when isolated areas of digital stiffness are identified. These techniques focus the patient's effort on specific joints. Wrist flexion, extension, radial, and ulnar deviation exercises are also taught. Some injuries, such as tendon lacerations, ligament ruptures, and fractures, require joint immobilisation or specific limitations on motion in the first few weeks. Early active range of motion is permissible in other injuries [44].

The final phase of hand and wrist rehabilitation is strengthening. Strengthening is performed once a functional range of motion is reached and after bone, tendon and ligament healing has happened. Several exercise products are available to assist in rehabilitating the injured hand. These products range from rubberband grippers and theraputty, used for strengthening grip and intrinsic and extrinsic hand musculature, to free weights, elastic tubing, Thera-Band, and weight-lifting equipment, used to strengthen the proximal larger muscles of the wrist, elbow and shoulder [44].

The work developed in this dissertation is a complement to the third phase of the rehabilitation process. It also contributes to the control of possible oedemas because it induces the patient to keep his hands elevated since the Oculus Quest cameras must recognise these.

# 3 STATE OF THE ART

Several games based on VR systems, robotic and haptic devices have been developed for hand rehabilitation with encouraging results over the last two decades. The systematic review performed in the first phase of the DSR process allowed identifying patients, technologies, equipment, and outcomes of this new hand rehabilitation process.

The performed systematic review organised and reviewed the functional outcomes and the effectiveness of applying AR/VR technologies for hand rehabilitation compared to conventional interventions. Of the 101 articles initially retrieved from the databases, only eight met the inclusion criteria defined for the review. The criteria were (1) articles must be written in English, (2) articles must be about VR or AR applications, (3) articles need to be specific for hand rehabilitation. The full text of the screened articles was examined if the study included (4) tests on at least ten patients with injuries or diseases which affected hand function, and (5) baseline or intergroup comparisons (AR or VR intervention group versus conventional physical therapy group).

From the included studies, two reported significant improvements in the intervention group, four stated improvements without significance in the intervention group and 2 reported similar results in both groups.

The selected studies' analysis allowed the identification of the patients' most common age groups. In seven of the eight studies (87.5%) patients were adults. Only one study focused on children and adolescents. This could be explained by the nature of the pathologies addressed in each study. Stroke is relatively rare in children and, even though the existing trends towards increasing stroke incidence at younger ages, the proportion of all strokes under age 55 was 18.6% in 2005 [46], [47]. Multiple sclerosis has its incidence peak around 30 years and occurs in 5% of cases after age 50 [48].

Despite the patient's age, few studies reported difficulties in handling the games and conducting the proposed therapy. Only four studies provided details about the patient's personal experiences during rehabilitation. One study stated that younger girls were more willing than the rest of the patients to undergo LMC training and frequently played LMC games for better functional results or other unknown reasons [49]. In another study, even though the participants were initially hesitant about computer games, after hands-on experience, all the subjects wanted to continue playing in the future [50]. In Da Silva Cameirão et al. [51], a self-report 5-point Likert questionnaire was carried out. In entertainment, patients rated the task with an average of 4.5 and considered it not too long, by rating it with an average of 1.2.

The task was easy to understand and scored 4.9. Patients scored the difficulty to control the virtual arms with an average of 2.1. For overall satisfaction, an average rating of 4.4 to continue the treatment was achieved. Lastly, Ganjiwale et al. [48] intervention group participants mentioned that the therapy was interesting and involving during informal talks.

The positive attitude towards using computer systems was a key element of the interventions and allowed to overcome the age barrier. One would think that children and adolescents are the groups where computer games' introduction would be more effective due to their predisposition to play [52]. Contrary to the hypothesis, all the selected studies' participants demonstrate a similar adoption to the proposed systems, regardless of age group.

The gender percentage of the participants was very similar, with no studies excluding patients based on gender. The overall rate of females (44.8%) was very close to males' percentage. A higher number of females was found in 50% of the studies. These results exclude the possibility of higher interactive systems adaptability based on gender.

From the eight articles that were included in the systematic review, one focused on Multiple Sclerosis [53], another on burns [49], a third article on fractures, crush injuries, or tendon injuries [54], and another on JIA, CP, and BPBI [55]. The remaining papers (four) dedicated themselves to test the AR/VR systems in stroke patients. This indicates that stroke is a major cause of hand and arm impairment. Stroke is a leading cause of mortality and disability worldwide, being a common cause for decreased hand function and strength [56], [57].

In 75% of the studies, the participants suffered from a specific pathology. In Tarakci et al. [55], there is a mention of applying and investigating the developed game's effects for rehabilitation in patients with different diseases as future work. Two of the selected articles tackled three other pathologies or injuries, with both showing similar results and no statistical differences between the intervention group and the conventional therapy group.

Motion sickness and adverse events due to watching stereoscopy videos or games have been reported in previous studies. The most common symptoms are visual fatigue, visual discomfort, eye strain, blurred vision, headache, dizziness, confusion, and disorientation [58]. From the included studies, one study [59] mentioned that one patient from the intervention group dropped out due to dizziness, which they said was unrelated to the intervention. Another study [55] reported no patient experienced intervention-related adverse events during intervention with Leap Motion Controller.

The systematic review considered less immersive VR systems in addition to the traditional Head-Mounted Displays, Powerwall screens, or Cave Automatic Virtual Environments. By expanding the inclusion criteria to include those systems, it was possible to observe that computers and 2D screens are the most used technologies and projections, respectively. All the hardware solutions presented in the selected articles use less immersive AR/VR systems. Studies with immersive AR/VR systems could not be included in the analysis since they did not meet the inclusion criteria (4) and (5). The inclusion of less immersive AR/VR systems is because these systems are convenient, easy to use, require no glasses or headsets with wires, less expensive, and easier to acquire. Fully immersive VR systems remain less available and costly, while displays are relatively cheap and easy to use [11], [19].

Each patient is different and requires specific treatment that addresses their individual needs. Most of the mentioned games integrate similar movements: finger flexion/extension, finger abduction/adduction, pinching with object grasp and release, and wrist flexion/extension. The physiotherapist’s role is to establish the correct amount of each exercise.

Hand movement tracking was made with four different technologies: LMCs, haptic gloves, video cameras, and haptic devices. Three of the four studies that focused on stroke patients had haptic gloves as the intervention delivery equipment. The evolution over time from the use of remote controllers to devices that provide freehand movements is clear. These hand movement trackers enable natural interactions. They allow actions of relevance with visible objects, replace typed commands by pointing actions on the items of interest, and give the patients control over the technology, avoiding complex instructions that complicate the interaction. From the solutions presented through the selected studies, only the RAPAEL Smart Gloves [59] and the LMC [49], [55] are currently available on the market.

Further studies on gathering accurate patient movements metrics may increase the scalability and facilitate healthcare professionals’ assessments by offering real-time results. Even though none of the selected studies took advantage of this feature, in Wu et al. [49], it is mentioned that the LMC provides validation of wrist flexion and extension and radial and ulnar deviation. This device is also reliable for assessing motor performance in pointing tasks and the reachable space from fingertip positions may be deduced by a computer.

Patients’ access limitations to rehabilitation, therapies, or physicians are problems that can be mitigated by remote rehabilitation, which can be achieved through videogames. In

Standen et al. [60], patients had the virtual glove in their homes and were advised to use the system for a maximum of 20 min. In, Broeren et al. [50], the system was used in a non-hospital environment (i.e. activity centre). Telemedicine-based on SkypeTM was used as a communication tool between the therapist and the personnel at the activity centre. In Wu et al. [49] and Tarakci et al. [55], the systems used were mentioned to be suitable for home-based hand or finger rehabilitation. In further studies, it would be interesting to evaluate if these systems can substitute traditional hand rehabilitation process and even completely change this process to be conducted at home.

Burke et al. [61] identified two game design principles with particular relevance towards rehabilitation: meaningful play and challenge. Five articles included in this review reported a positive relationship between patients' motivation and the use of interactive computer systems for rehabilitation with challenge. In Da Silva Cameirão et al. [51] and Shin et al. [59], the designed system can adjust tasks' difficulty according to participants' performance. In Standen et al. [60], Broeren et al. [50], and Ganjiwale et al. [54] the games were designed to be constantly challenging, with increasing levels of difficulty. This challenge provides an improved feeling of achievement upon completing tasks and, consequently, leads to positive reinforcement.

AR/VR systems are motivators for patient adherence, but their effectiveness still needs confirmation. On the other hand, conventional rehabilitation was already proven to provide positive results. Six studies combined AR/VR-based rehabilitation with standard occupational therapy. The other two compared the impacts of intervention therapy against conventional therapy by only providing one or the other therapy forms to patients. To the extent that the studies have been evaluated, AR/VR technologies only can complement the traditional hand rehabilitation process.

An interesting topic for future research would be to compare AR versus VR's applicability. With the selected studies it was not possible to compare AR with VR and assess which of the technologies has a higher relevance since one of the chosen studies followed under the category of see-through AR display while the other seven under the category of monitor-based VR display [58].

Equipment conformity is paramount for any hand rehabilitation approach to reach common practice. This aspect was not mentioned in any selected studies but represented a very important section that should be mentioned in further studies.

All studies focused on games as motivators and physical/motor rehabilitation providers for exercising individually. None of the selected studies mentioned collaborative or competitive gameplay, even though it is well known that co-player and multiplayer games have a strong potential to increase patient's motivation and engagement [62], [63].

Goršič, Cikajlo, and Novak [64] described the effects on motivation and exercise intensity with competitive and cooperative arm rehabilitation games. Of the 29 patients involved in the study, 12 chose the competitive game as their favourite, 12 picked a cooperative game, and five preferred to exercise alone. This study concluded that competitive games have a higher potential than conventional rehabilitation exercises to lead to functional improvement and increased patients' quality of life. Cooperative games do not increase exercise intensity but could still increase the motivation of patients who do not enjoy the competition.

The AR/VR games from the analysed studies provided similar results regarding hand function improvements. Most of the studies (75%) reported improvements in the intervention group and the others (25%) showed no statistical differences between the intervention group and the conventional therapy group. These results suggest that AR/VR game systems can be used as a complement to traditional therapies. Also, these systems can be operated remotely allowing extra rehabilitation sessions. Findings from Lopes et al. [65] complement this statement since they also suggest that games are used as a complement to conventional therapies and not as a substitute. These games promote patients' engagement in the treatment and optimise therapeutic gains.

The review results showed that AR/VR systems could be used as complementing tools to enhance hand rehabilitation and motor retraining. Specifically, the review showed that (1) people seem capable of neuromuscular re-education through less immersive virtual environments; (2) movements learned in AR/VR environments can be transferred to real-world equivalent tasks in most cases, and in one case even generalise to untrained tasks; (3) age and gender do not appear to be an impediment; (4) in the few studies (n=8) that have compared hand rehabilitation in real versus augmented/virtual environments, advantages for AR/VR training have been found: these systems can provide engaging task-oriented exercises, as well as visual and auditory feedback regarding performance and gain; engages players to increase the rehabilitation intensity; simple systems such as LMC and haptic gloves are easily integrated into the home setting.

A few findings from the review provide drivers and relevant design elements for AR/VR development and introduction in hand rehabilitation, namely: (1) give feedback on performance to the patients; (2) individually adjusted constant challenge and increasing levels of difficulty; (3) increasing difficulty can be done by a higher number of movement repetitions, and a higher required precision to complete a task.

As was previously mentioned, studies with immersive AR/VR systems could not be included in the analysis since they did not meet all the inclusion criteria points.

Numerous input devices were found in the literature to capture hand movements, gestures and fingers' position being some of them: haptic devices [50], [54], [66], [67], video cameras [10], [53], [68], electronic/virtual gloves [51], [59], [69]–[72], Microsoft Xbox 360 Kinect sensor [73]–[75] and LMC [49], [55], [76], [77]. Devices such as sensing gloves have even been combined with video cameras [78], the Xbox 360 Kinect [79], [80], PlayStation 3 [81], [82], and Oculus Rift [83]. These systems provide accurate metrics of patients' performance. However, most of them require the patients to use a glove, an exoskeleton, or a device in direct contact with the hand. This makes it impossible for some patients with open wounds or other disfigurements to use these systems, excluding them from this rehabilitation alternative.

Some studies with immersive AR and VR systems were excluded for not meeting the systematic review's inclusion criteria. Devices such as AR HMD [84], VR HMD [85], shutter glasses (RealD Professional CrystalEyes 5) [86], Cave Virtual Environment [87], and Cy-VisorDH-4400VP HMD [88] were found in the literature as viable devices to provide complete immersive environments and the improvement of compliance, engagement, and even amusement of patients.

# 4 SPECIFICATIONS

## 4.1 OVERVIEW

In this thesis, a VR serious game is proposed to improve hand rehabilitation and physiotherapy. The main aim is to develop an engaging and efficient solution that enthusiasts patients with hand impairing conditions to play the game and perform movements that will assist in their rehabilitation process.

During the investigation process, there was a need to define the system and the game's requirements and goals. Furthermore, from the conventional hand exercises, mentioned in the Hand Rehabilitation subsection of the Background, we had to select some gestures to introduce in the game and start developing it. Finally, the game flow plays a significant part in a game's success. The StableHand VR game's game flow was studied and defined to provide a consolidated experience.

The game's requirements, introduced gestures and game flow are presented in this section.

## 4.2 REQUIREMENTS

During hand rehabilitation sessions, patients are asked to perform a specific set of tasks. These tasks must be adapted to the patient's needs and are often a one-on-one process between the physiotherapist and the patient. The physiotherapist evaluates factors such as patient's current and past activities, goals, functional strength, sensation, range of motion, coordination, scar tissue characteristics, pain, and signs and symptoms of healing to determine the most suitable methods for the patient's rehabilitation process. Also, treatment plans frequently involve contraindications of certain movements [73].

StableHand VR is a serious game for hand rehabilitation created to fulfil the following requirements:

- Detect single finger and hand position movement;
- Recognise gestures;
- Provide a broad set of hand rehabilitation exercises;
- Record evaluation parameters and provide accurate statistics;
- Make game generated data available to patients, therapists and physicians;

- Achieve high levels of motivation and engagement;
- Easy to use;
- Suitable for use by a wide range of patients, including patients with malformations;
- Improve patients’ hand mobility and autonomy in daily tasks;
- Patients’ being able to practice movements by imitation and repetition;
- Offer an immersive and entertaining experience while under treatment.

The developed system needs to accurately detect fingers, hand position and movements and recognise gestures. Patients in physiotherapy must do repetitive exercises and specific tasks to regain hand function, which also needs to be achieved in the game. One of the advantages of using a game that can follow and record finger and hand position over time is the possibility of using these measures and parameters to evaluate patients’ state and evolution. Providing accurate statistics allows the physiotherapist to adapt the rehabilitation to the patients’ state both in real-time and between sessions.

Physiotherapy sessions can bring discomfort to patients. This underlines the need for a motivating and engaging system that can immerse and distract the patient from the difficult and repetitive nature of physiotherapy exercises. The developed game must be accessible and appealing to patients from diverse backgrounds and with different capabilities, considering that most patients have never used VR systems, and many do not play computer games. Therefore, StableHand VR must be intuitive, efficient, easy to navigate and interact. The system must recognise the hand and gestures made by several patients suffering from different disabilities, including patients with malformations.

## 4.3 HAND GESTURES INTERACTIONS

Hand therapy rehabilitation requires the patient to do a specific set of repetitive movements, such as moving the finger up and down, bend and extend the fingers with single/multi-finger contraction, grab and pinch. These are the basic hand movements required for daily living.

The new version of the Oculus Integration SDK (v12) allowed hand tracking implementation in the StableHand VR game and provided several ways for the hands to be rendered. The hand tracking API exposes a filtered pointer pose and pinch gesture detection.

Seven gestures/movements were selected for the player to be able to interact with game elements: poke, pinch, pinch grip, sequential pinch, flexion and extension, radial and ulnar deviation, and pronation and supination. These gestures are normally used in physiotherapy sessions and are shown in Table 4-1, along with their definition and representation.

Table 4-1. Gestures implemented in StableHand VR

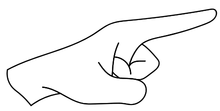
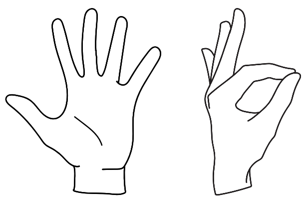
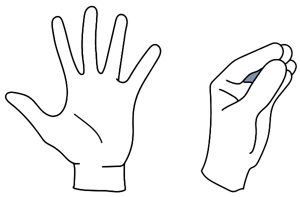
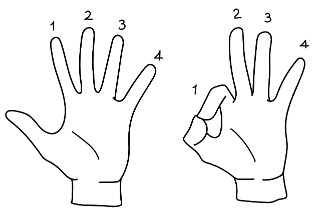
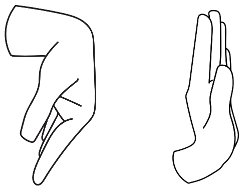
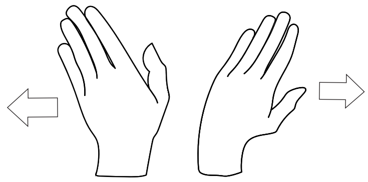
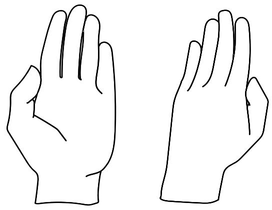
| Denomination | Definition | Gesture representation |
|---|---|---|
| **Poke** | Poke is the movement of extending only one finger (in this case, the index finger). |  |
| **Pinch** | Pinch is the movement when the thumb fingertip touches the index fingertip (or another fingertip). |  |
| **Pinch grip** | Pinch grip is the movement of closing the hand by touching all the fingertips. |  |
| **Sequential Pinch** | Sequential Pinch is the movement of touching with the thumb fingertip all other fingertips. The order followed was index, middle, ring, and pinkie, as shown in the numbers of the gesture representation. |  |

Table 4-1. (continued).

| Denomination | Definition | Gesture representation |
|---|---|---|
| **Flexion and Extension** | Flexion is the movement of bending the palm down, towards the wrist. Extension is the movement of raising the back of the hand. |  |
| **Ulnar and Radial Deviation** | Ulnar deviation is the movement of bending the wrist to the little finger. Radial deviation is the movement of bending the wrist to the thumb. |  |
| **Supination and Pronation** | Supination is the movement of turning the palm upwards. Pronation is the movement of turning the palm downwards. |  |

After understanding how each gesture is performed in conventional rehabilitation, it was planned to implement it through pseudocode, a technique which uses short phrases to explain specific tasks within a program.

The Oculus Integration SDK already implements the poke and pinch gestures, leaving only the interactions to be implemented. These interactions only needed to be implemented. The planning of the remaining gestures defined and represented in Table 4-1 was described in pseudocode.

Figure 4-1Figure 4-3 shows the pseudocode for the pinch grip gesture, Figure 4-2 for the sequential pinch gesture and the pseudocode for the pronation and supination gesture is shown in Figure 4-3.

```
• Initialize variable start to a value of false
• Initialize variable hand to a value of 0
• If the start variable is false (the movement as not been initiated), then
    • If there was simultaneously a pinch between the thumb and the index
      fingers, the thumb and the middle fingers, the thumb and the ring fingers
      and the thumb and the ring fingers, then
        • Change start variable value to true (the movement is initiated)
        • If the left hand was used to perform the movement
            • Maintain hand variable value of 0
        • If the right hand was used to perform the movement
            • Change hand variable value to 1
        • Wait until there is no longer a pinch between thumb and the index
          fingers, the thumb and the middle fingers, the thumb and the ring
          fingers nor the thumb and the ring fingers
        • When the pinch is no longer recognized (the movement is considered as
          completed)
            • Change start variable value to false
            • There is an interaction with game objects
```

Figure 4-1. Example pseudocode for the pinch grip gesture.

- Initialize variable start to a value of false
- Initialize variable hand to a value of 0
- If the start variable is false (movement as not been initiated), then
  - If there was a pinch between the thumb and the index fingers, then
    - Change start variable value to true (the movement is initiated)
    - If the left hand was used to perform the movement
      - Maintain hand variable value of 0
    - If the right hand was used to perform the movement
      - Change hand variable value to 1
    - Wait until there is a pinch between the thumb and the middle fingers
    - When the pinch is recognized
      - Wait until there is a pinch between the thumb and the ring fingers
      - When the pinch is recognized,
        - Wait until there is a pinch between the thumb and the pinky fingers
        - When the pinch is recognized
          - Change start variable value to false
          - There is an interaction with game objects

Figure 4-2. Example pseudocode for the sequential pinch gesture.

```
• Initialize variable start to a value of false
• Initialize variable hand to a value of 0
• If the start variable is false (movement as not been initiated), then
  • If the palm turns up and reaches a certain minimum range, then
    • Change start variable value to true (the movement is initiated)
    • If the left hand was used to perform the movement
      • Maintain hand variable value of 0
    • If the right hand was used to perform the movement
      • Change hand variable value to 1
    • Wait until the palm turns down and reaches another defined minimum
      range
    • When the minimum range is achieved
      • Change start variable value to false
      • There is an interaction with game objects
```

Figure 4-3. Example pseudocode for the pronation and supination gesture.

The pronation and supination, the flexion and extension, and the radial and ulnar deviation gestures are all comprised of a sequence of two movements: turning the palm upwards and downwards, bending the hand down and raising it back up, and bending the wrist to the little finger and afterwards to the thumb, respectively. Because of this similarity, the pronation and supination gesture's pseudocode was adapted for the other gestures.

For the flexion and extension gesture, instead of checking if the palm turns up, the system will check if the hand bends down until it reaches a certain minimum range. Instead of waiting for the palm to turn downwards, the system will wait for the hand to be raised until it reaches a minimum range.

For the ulnar and radial deviation gesture, instead of checking if the palm turns up, the system will check if the wrist has bent to the little finger until it reaches a certain minimum range. Instead of waiting for the palm to turn downwards, the system will wait for the wrist to be bent to the thumb until it reaches a minimum range.

## 4.4 GAME FLOW

The core of game flow is the formal study of how interacting choices produce outcomes. The flow of a game can be seen as the “player experiences overtime” and defines what the players can do in the game at certain parts of the game.

One part of game flow is the mental state of game interaction where the player is fully immersed. In his work, “Flow: The Psychology of Optimal Experience” [89], Mihaly Csikszentmihalyi theorises that the flow state is an ideal state of intrinsic motivation where players are happiest. Elements such as rewards, clear goals, loss of consciousness, loss of sense of time, direct and immediate feedback, and the balance between player skills and challenge can influence and affect a game’s flow.

Another part of game flow is designing the environment to direct the player on to the next step naturally. This flow can be presented by a UI diagram that shows the overall flow of everything the player can do and how the interactions can be performed.

After initialising the game, the player is presented with the Tutorial screen to start the tutorial, change to the multi-language menu screen, or the main menu screen. The player can change the game’s language between English, Portuguese or German in the multi-language menu screen. The player can also return to the Tutorial screen or change to the main menu screen. In the main menu screen, the player can start the main gameplay scene, change to the tutorial scene or the multi-language menu scene, and quit the game. Lastly, in the main gameplay scene, the player can interact with the stipulated objects and decide to leave the game at any time. The flow diagram of the main gameplay scene can be seen in Figure 4-4.

After initialising the game, the player is placed in the middle section, where an exit button is located. From there the player can teleport freely to the other three areas: Crops, Milk, and Cheese. Each of these sections has specific tasks that can be performed. There is a preferable order for the tasks to be completed. However, the player can perform these tasks as he desires. There are a few tasks that can only be performed after other tasks have been completed. These tasks are the ones that follow the double arrows presented in Figure 4-4. For example, cooking the vegetables in the Cheese section can only be performed after ten vegetables are picked up and placed in a stipulated place. Even if a task is not completed, the player can change sections and tasks.

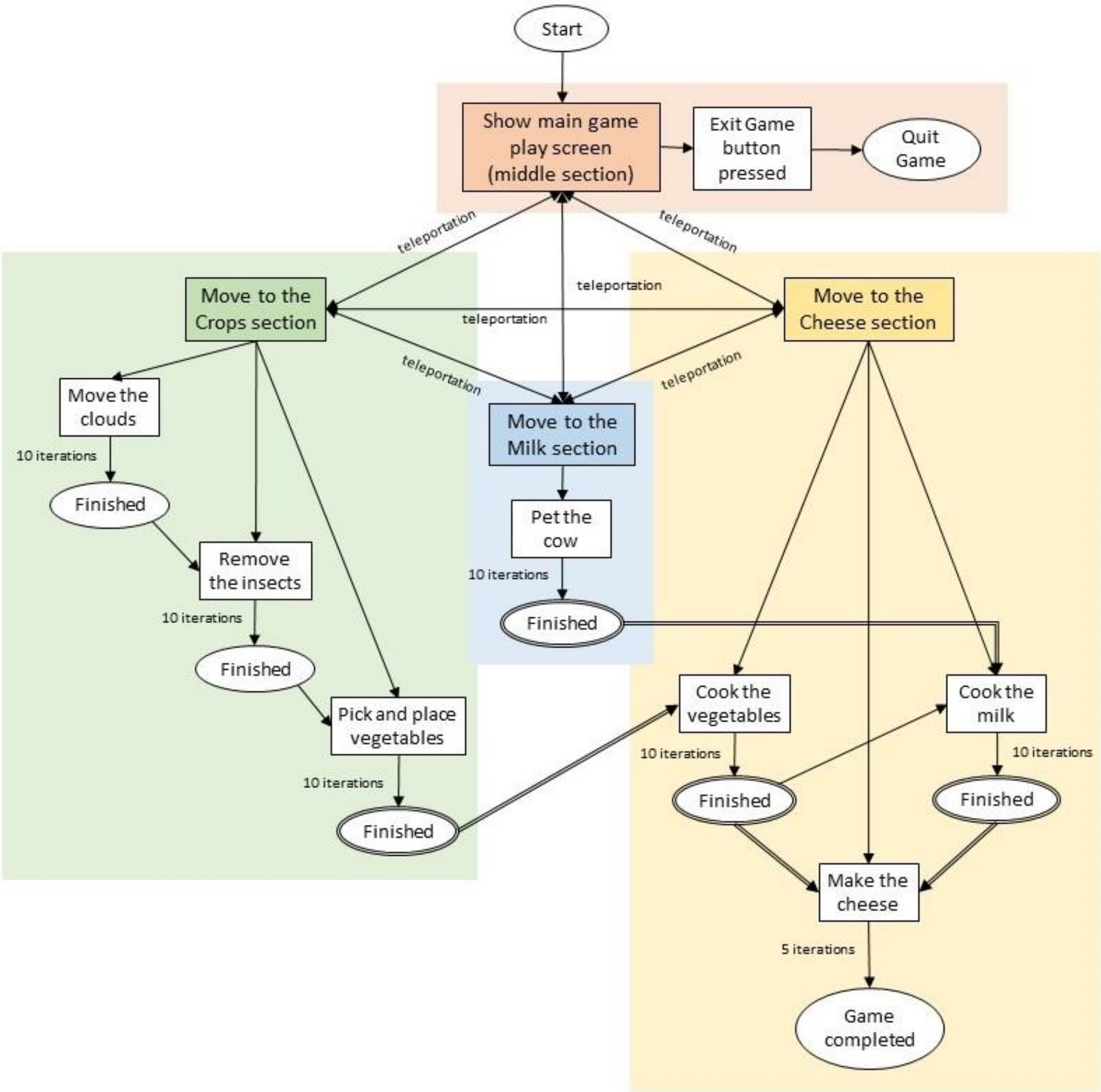



Figure 4-4. Flow diagram of the main gameplay scene.

# 5 IMPLEMENTATION

## 5.1 HARDWARE AND SOFTWARE SOLUTIONS

Many of the hardware solutions presented in the State of the Art could be used to meet the stipulated requirements, given that all can detect hand or finger position and movement, recognise gestures, provide repetitive tasks, record evaluation parameters and provide accurate statistics. Even though all the mentioned systems offer many possibilities for games to improve patients' motivation and engagement, a VR system brings an immersive sensation to the rehabilitation. VR devices combined with the LMC provide an immersive form of rehabilitation but lack the easiness of use due to the need for cables and connections between the VR system and the LMC. A hardware solution with physical gloves would not be comprehensive since it would exclude patients with open wounds or deformities of the hand to use the system.

Based on the literature analysis and the evaluated systems, the Oculus Quest headset, shown in Figure 5-1, emerged as a technological solution that met the stipulated requirements and showed the distinctive advantage of being completely wireless: no extra hardware is needed for hand tracking. Overall, it is the economic, engaging and non-invasive solution that we were searching.

The Oculus Quest HMD performs hand tracking and displays/delivers the game. This device is cost-efficient and time-efficient. It is time-efficient since there is no need for initial camera and system calibrations. It is cost-efficient since it only requires one component currently available on the market and allows patients to play in their home. Since participants will be able to go under treatment and perform physical therapy from their homes' comfort, this can drastically cut the number of trips to the clinics/hospitals, representing a decrease in the treatment costs.

Furthermore, this device has an SDK for development in Unity3D, the Oculus Integration asset, which includes a hand and finger tracking API. Unity was the chosen engine to develop the VR serious game for hand rehabilitation.

Figure 5-1. Oculus Quest. Image downloaded from https://www.oculus.com/quest/ in January 2020

Unity3D is a cross-platform three-dimensional engine and a user-friendly development environment. This real-time development platform lets artists, designers, and developers create two-dimensional, three-dimensional, augmented reality and virtual reality games, as well as simulations and other experiences.

## 5.2 DATABASE

The unity engine also allows the integration of several databases. The chosen database to integrate in the game was the SQLite, a self-contained, serverless, zero-configuration, transitional SQL database [90]. SQLite was chosen because of the following:

- Recommended by Android official documentation;
- Easy setup and integration with Unity and Android (Oculus Quest is an Android-based device);
- Is lightweight;
- Consumes less resources;
- Is a locally stored database;
- Easy to view database structure and contents with the free SQLite Browser;
- Maintains state over sessions (since it is locally stored).

An initial survey of useful parameters for health professionals to analyse was carried out to achieve feasibility and success during the database implementation. The Oculus Quest system's feasibility in recording those parameters was also studied.

The pre-established parameters to record were the following: range of motion, total duration of the exercise, single duration of activities, single duration of levels, frequency of a movement, number of follow-ups (if first attempt of gripping is not successful), and time to reach the exercise goal.

According to these parameters, the conceptual model was elaborated on the TerraER platform to simplify the database's implementation, data visualisation, and understand the real world's entities and how they interact with each other. The conceptual model developed within this project is presented in Figure 5-2

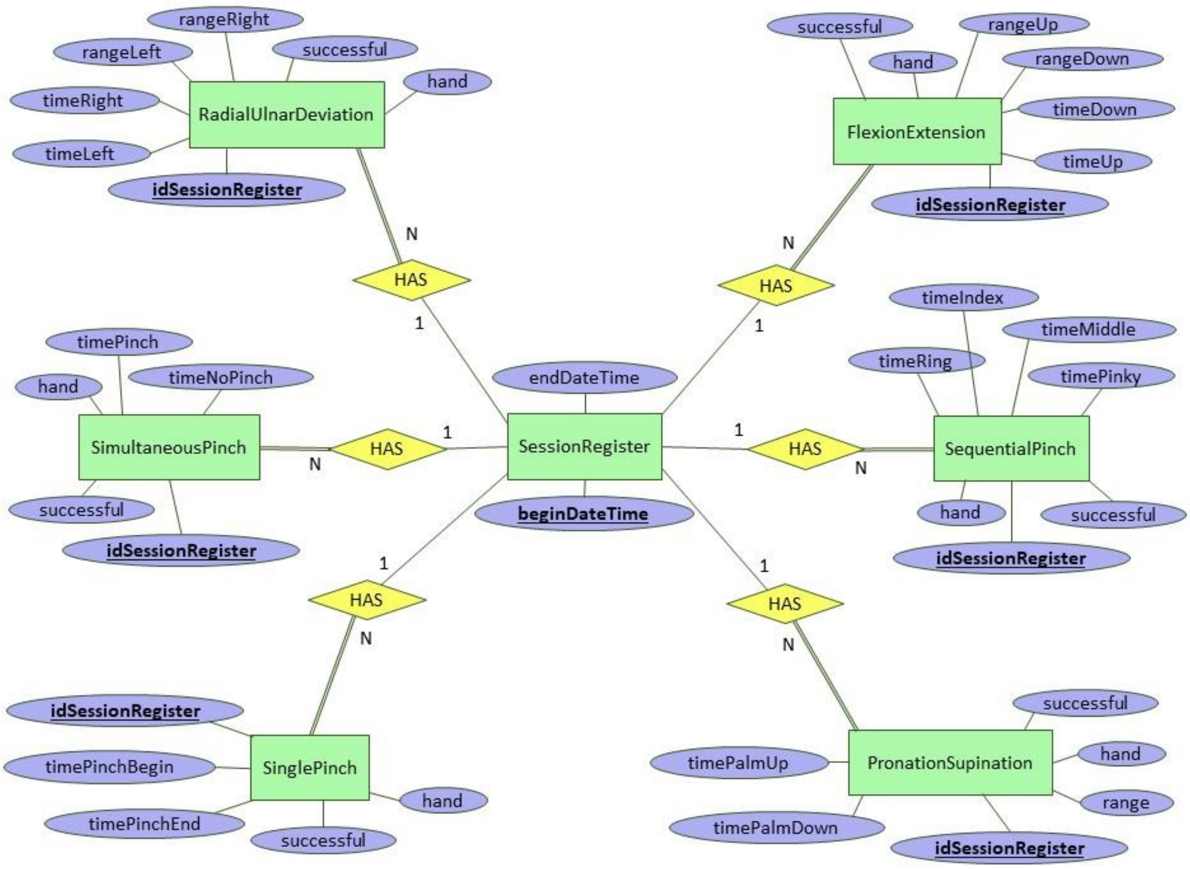



Figure 5-2. Conceptual model adopted in the StableHand VR game.

The conceptual model consists of schematising the necessary data to use in the applications, but not its processing flow or physical characteristics. Entities, relationships, and attributes form it. The entities are objects on which it is intended to store information. Relationships consist of associations between entities, established according to management needs. Finally, attributes are elementary data that characterise entities and relationship entities.

Based on the parameters to record, the entities were primarily defined as the players' movements: radial and ulnar deviation, simultaneous pinch, single pinch, flexion and extension, sequential pinch, and pronation and supination. Another entity defined was the Session Register that would have the date and time of the game start and game end as attributes.

All the entities that represent the movements have as attributes the identification of the session (i.e. the date and time of when the game was started); the hand used to complete the movement (right or left hand); and the success rate of the action (i.e. how many times the movement was correctly completed). The other attributes represent the range of the movements made and the duration until completion.

Once the conceptual model was developed, it was converted to the respective logical model. Thus, the MySQL Workbench database management tool was used, obtaining the model in Figure 5-3.

In the first phase, each of the conceptual model entities was represented by a table, with its corresponding attributes. For each one of these attributes, its format was selected and its characterisation was made. The characterisation was made by referring if they are not null attributes (i.e. if it is mandatory to fill them out, shown in Figure 5-3 as a full painted rhombus) and if they are primary key for the key attributes (shown in Figure 5-3 as the yellow key). The red rhombus identified as the "idSessionRegister" represents a Foreign Key that connects the table representing the movement/gesture to the Session Register table.

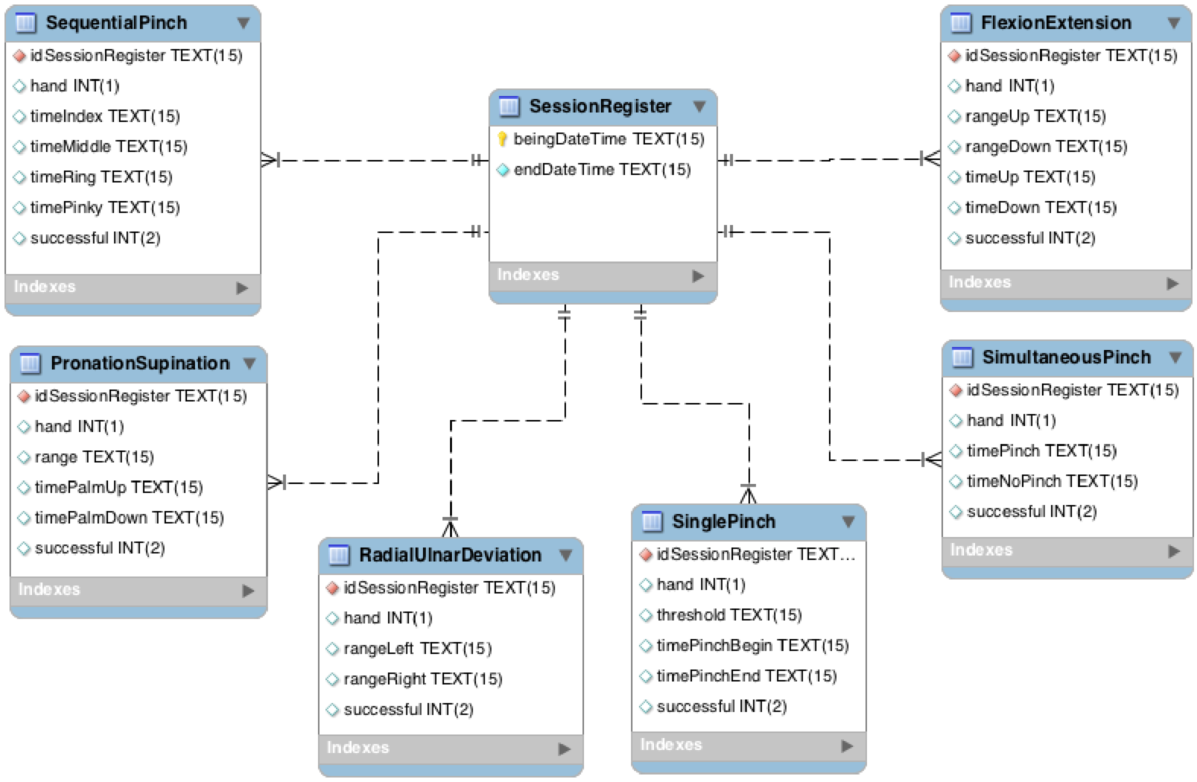



Figure 5-3.Logical model adopted in the StableHand VR game.

After creating the logical model, the physical model was created inside the StableHand VR application. There were some difficulties experienced during the database implementation. First, there was the need to alter the Android permissions of reading and writing on the device. These permissions were added in the Android manifest. The second difficulty was in accessing the database file. The database file in the Oculus Quest is created inside the headset's sandbox, which means that direct access is not possible. The solution is to copy the database file to the external storage when the player comes in contact with the exit. In this way, the SQLite database's physical model can be directly accessed through its DB Browser after the headset is restarted. The path to access the database file is: Quest > Internal shared storage > Android > data > com.BGKlinik.StableHandVR > files > Database.

The code generated for creating the tables, an initial step of the physical model, can be seen in the appendix A – Database Tables creation of this work. If they did not exist yet on the database file, the tables would be created when the application opened.

Finally, the tables' data insertion is performed inside the StableHand VR game during playtime. The database must be constantly updated to be as efficient as possible, and there is also a transaction that allows data insertion in the tables. This transaction and the code to generate it for each movement can be seen in Appendix B – Database Tables population.

## 5.3 GAME DESIGN

The StableHand VR game intends to give players the sensation of being immersed in a calm, outside environment, to which most people could relate to and feel interested in exploring the space around them. On the other hand, the environment cannot be over-simplistic because it must provide enough contextualized interaction elements to support the rehabilitation tasks. Several popular scenarios were investigated to achieve such an environment, but soon the farm setting was revealed to be the adequate scenario to give players the sensation of being immersed in a calm, outside environment.

The game's name was created and suggested by one of the project supervisors as an allusion to two different concepts: stableman and stable hand. The first concept is related to the chosen farm setting and the second to one of the final goals for the patients to achieve: a stable (i.e. steady) hand capable of performing daily life tasks with confidence.

First ideas and drawings for the setting and tasks are shown in Figure 5-4a and Figure 5-4b. Figure 5-4a presents clouds and rain, crops, and a windmill. The interaction between the three objects would be turning the windmill to make wind that would move the clouds. Once the clouds are on top of the crops, a different movement to make it rain. Once it rained on the crops, they would be ready for picking (with a different action). The progress bars were thought to be introduced as indicators for the patients. The differences between the Figure 5-4a and Figure 5-4b resides in the addition of a cow to pet and icons that would show which tasks the player should perform next.

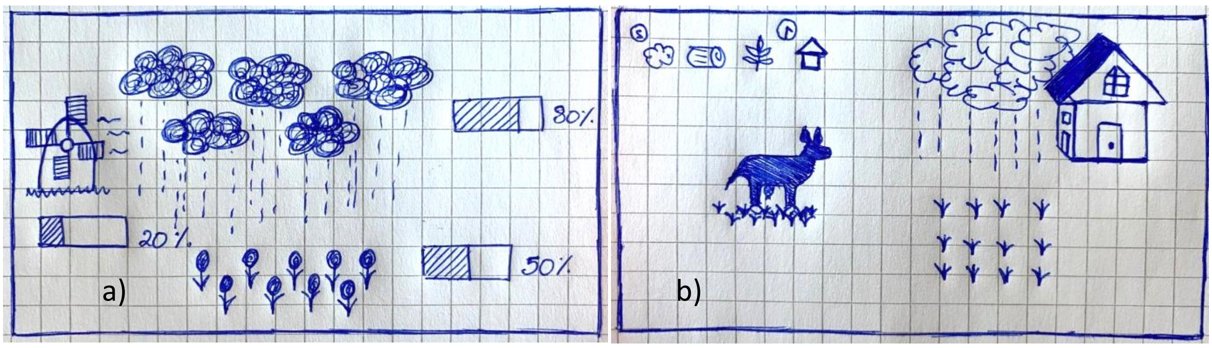



Figure 5-4. First drawings and ideas for StableHand VR: a) first sketch; b) second sketch.

A simple concept for a game storyline was thought out to enhance the experience of playing the game, to give patients a line of reasoning through the game and autonomy to decide which tasks they wanted to perform. In the game's farm environment, there are three main sections of interaction: the Crops section, the Milk section, and the Cheese section.

The three sections' main idea is that the patient gathers all the ingredients and makes all the processes needed for making cheese. The player will have to make it rain on the crops, remove insects from the crops, collect the vegetables, milk the cow, cook the vegetables and the milk. These tasks should be performed in this order, but the player may choose otherwise to give a feeling of freedom and autonomy.

The StableHand VR environment was created using several Unity Asset Store assets. These assets were modelled and conjugated to represent the desired sections best.

## 5.4 GAME CYCLE

The first focus of the game implementation was the creation of a structured Game Cycle, presented in Figure 5-5. Figure 5-5 displays the set of interactions available for players to reach the final goal in each of the three defined sections. Direct interaction with game objects and sound effects was implemented to enhance attention and motivation and provide immediate feedback.

The Game Cycle of StableHand VR follows the order shown by the arrows of Figure 5-5. Ideally, the player should start by moving the clouds in the Crops section, then remove the insects from the ground and in the end, pick up the vegetables and place them in a box. After this, the player should teleport to the Milk section and pet the cow. The player can start the Cheese section's tasks only after completing the Crops and Milk sections' tasks. In this section the player should start by cooking the vegetables, cooking the milk, and finally, making the cheese.

Only certain game tasks are dependent on the completion of other tasks, for instance, to have vegetables in the Cheese section the player needs to collect ten vegetables from the Crops section. Still, the player can start removing insects without finishing moving the clouds. This feature was introduced to provide freedom of choice and enhance players' autonomy. The player can start a task and change to a different task if he feels tired with the constant possibility of returning to the unfinished task.

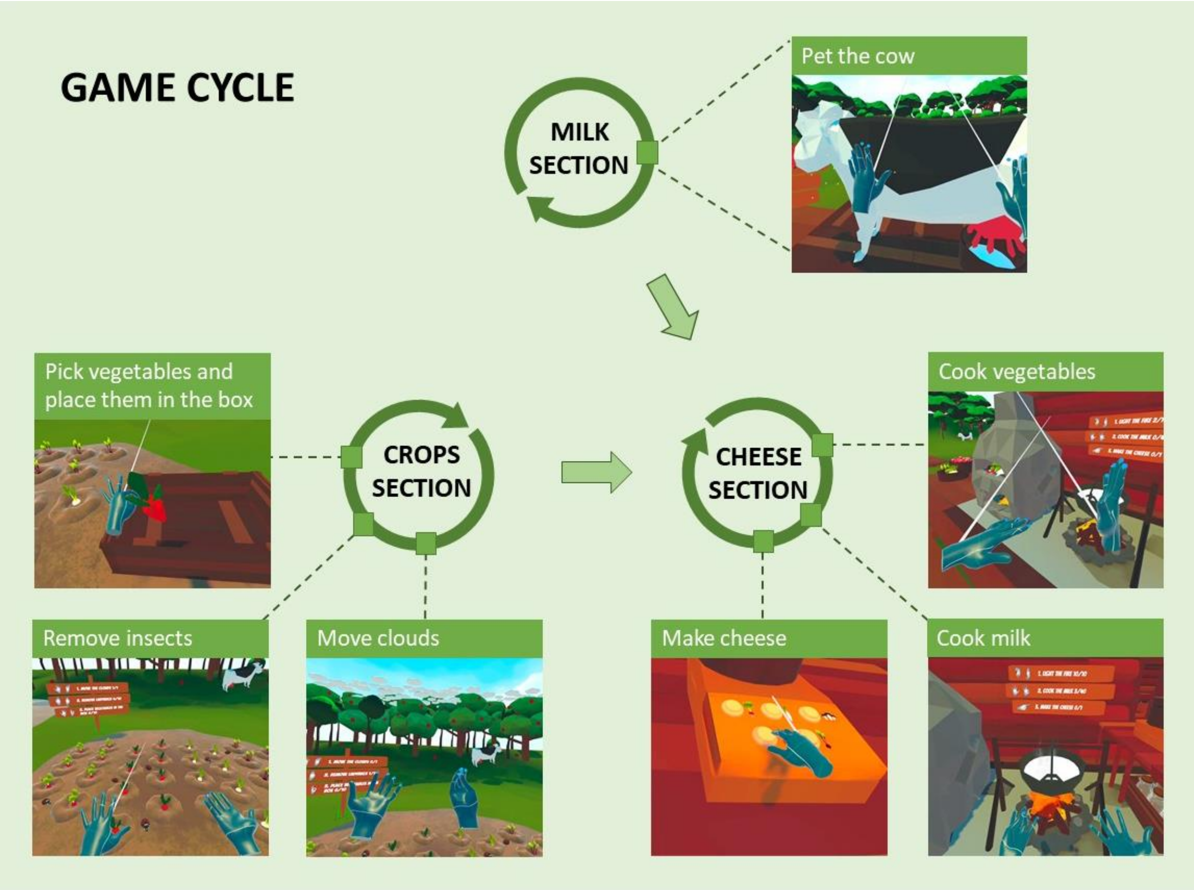



Figure 5-5. StableHand VR game cycle.

The interactions shown in Figure 5-5 can be called near-field interactions. In near-field interactions, the components are within arm's reach. This interaction uses a direct method for the players' hands to interact with the objects. On the other hand, in far-field interactions, the components are beyond the arm's reach and to interact with them the player needs to raycast or move closer to the element to make it a near-field component. Far-field interactions were also implemented in the game for the player to teleport between sections.

## 5.5 GESTURES AND GAME INTERACTIONS

Another important focus of the game implementation was to assign each movement described in section 4.3 Hand Gestures interactions with tasks to be performed in each section. For each task to be completed, the assigned movement/gesture needs to be repeated a certain amount of times by the player. The physiotherapist should define this repetition in light of the disability of the patient.

The gestures were implemented in C# language and the tasks were assigned to the movements as follows:

(1) The poke gesture: for the interaction with the buttons in the menu and make the cheese, in the Cheese section. The cheese appears after pushing the button, as shown in Figure 5-6.

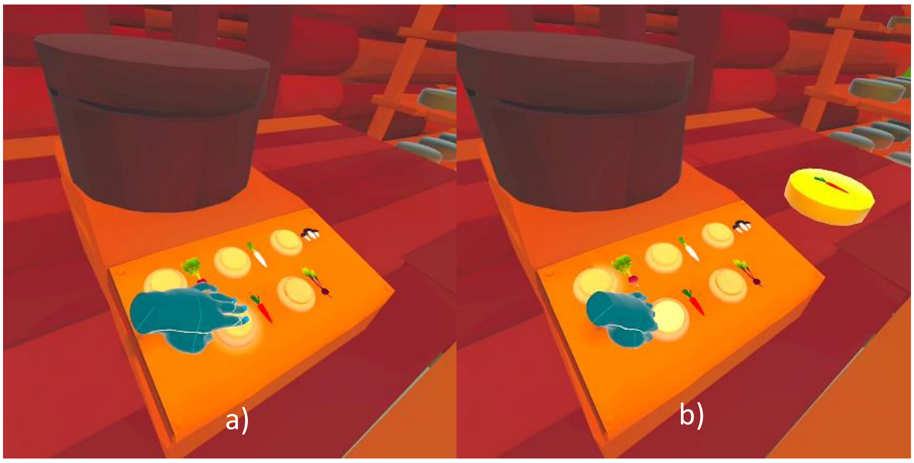



Figure 5-6. Poke interaction to make the cheese: a) before pushing the button; b) after pressing it.

The poke interaction was implemented using the OculusSampleFramework namespace provided by the Oculus Integration asset. There are three states when interacting with an object: contact state (touch), proximity state (near-touch), and action state (action after contact). The poke interaction occurs when a finger's fingertip interacts with an object defined as interactable through the action state.

(2) The pinch gesture: to pick up vegetables and put them in the box, in the Crops section. This interaction can be seen in Figure 5-7. The player pinches to pick up the vegetable and stops pinching to release.

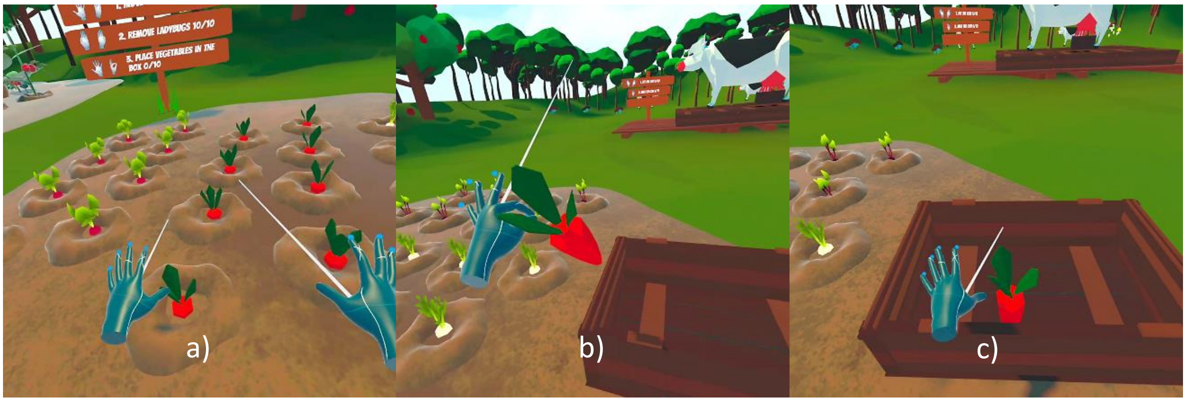



Figure 5-7. Pinch gesture to interact with the vegetables: a) before picking up the vegetable; b) pinching to grab; c) stop pinching to release.

The pinch interaction was implemented using the OculusSampleFramework and extending the OVRGrabber class. If the player is not grabbing any object, the pinch strength (defined by the space between the thumb and index fingertips) is greater than a specified threshold and grabbable candidates exist, the pinch begins. The pinch ends if the player is grabbing an object and if the pinch strength is not greater than the defined threshold. The items to grab need to be defined as grabbable, have colliders and rigid bodies. When grabbed, a grabbable object acquires the transform position of the hand that is holding it.

(3) The pinch grip gesture: to move the clouds from the back to the front and stand over the vegetables, in the Crops section. The clouds move closer to the vegetables' field until it rains, and the vegetables grow, making them easier to pick up. With each sequence of opening and closing the hand, the cloud object changes its position as presented in Figure 5-8.


Figure 5-8. Pinch grip movement to interact with the clouds: a) palms up to begin; b) pinch grip; c) open hand to finalise the movement and move the clouds.

The pinch grip gesture was implemented by first checking if the movement was already started. If the action was not initiated, the system would check for a pinch in all the fingers simultaneously and consider the movement as initiated if the grip pinch occurred. Lastly, the system waits until the pinch grip is broken and considers the movement as not initiated.

(4) The sequential pinch gesture: to cook the milk, in the Cheese section. The milk starts boiling with the first pinch, and it keeps boiling until the task is completed with the last pinch, as shown in Figure 5-9.


Figure 5-9. Sequential pinch movement to cook the milk: a) Before the movement was started; b) after starting the movement with the milk boiling.

The sequential pinch's implementation follows a similar order as the grip pinch. First, the system checks for an index pinch if the movement was not initiated. When that pinch is found, the movement is considered initiated, and the system will wait until a pinch with the middle finger is performed. The middle finger pinch is followed by a pinch with the ring finger and lastly with the pinkie finger. The movement is then considered as not initiated and can be repeated.

(5) The flexion and extension movement: to start the fire and cook the vegetables, in the Cheese section. The fire rises after the first flexion and extension is completed to cook the vegetables and decreases near the last flexion and extension. This interaction can be seen in Figure 5-10.


Figure 5-10. Flexion and extension movement to cook the vegetables: a) flexion to start the movement; b) extension to finalise.

The flexion and extension interaction was implemented by checking the hand's transform orientation. If the movement is not considered initiated, the system will check if the hand's transform in the vertical axis (axis right.y) is lower than a defined range. When that happens, the movement will be considered initiated. The system will wait until the hand's transform in the vertical axis is greater than another defined range. The movement is regarded as not initiated and can be repeated.

(6) The ulnar and radial deviation movement: to pet the cow, in the Cow section. The cow radiates energy and happiness in the form of light particles. In each cycle of ulnar and radial deviation, the particles are spread, as presented in Figure 5-11. In Figure 5-11b, some of the particles released are signalized.

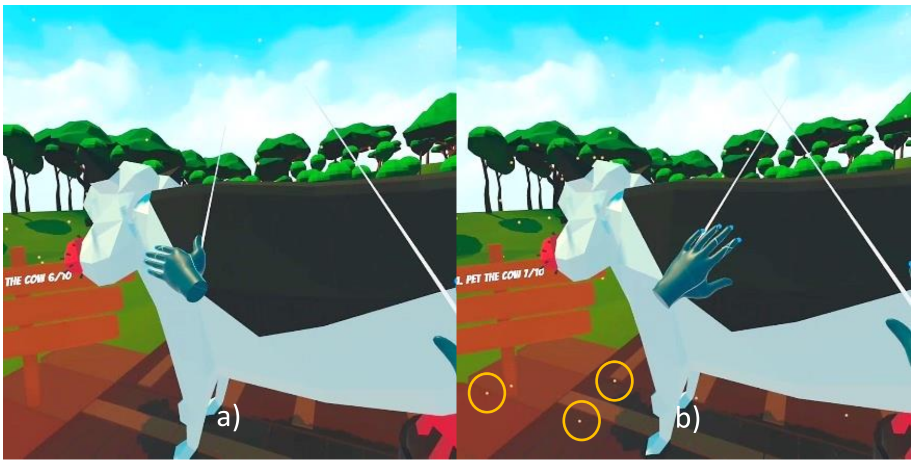



Figure 5-11. Ulnar and radial deviation to pet the cow: a) ulnar deviation to start the movement; b) radial deviation to finalise.

The ulnar and radial deviation interaction was implemented following the same reasoning as the flexion and extension interaction. The difference consists of the axis that is checked and the defined ranges. The axis checked in this interaction is also vertical but in a different coordinate (axis right.z).

(7) The supination and pronation movement: to remove the insects from the vegetable field, in the Crops section. The ladybugs disappear one by one after each supination and pronation cycle, as shown in Figure 5-12.

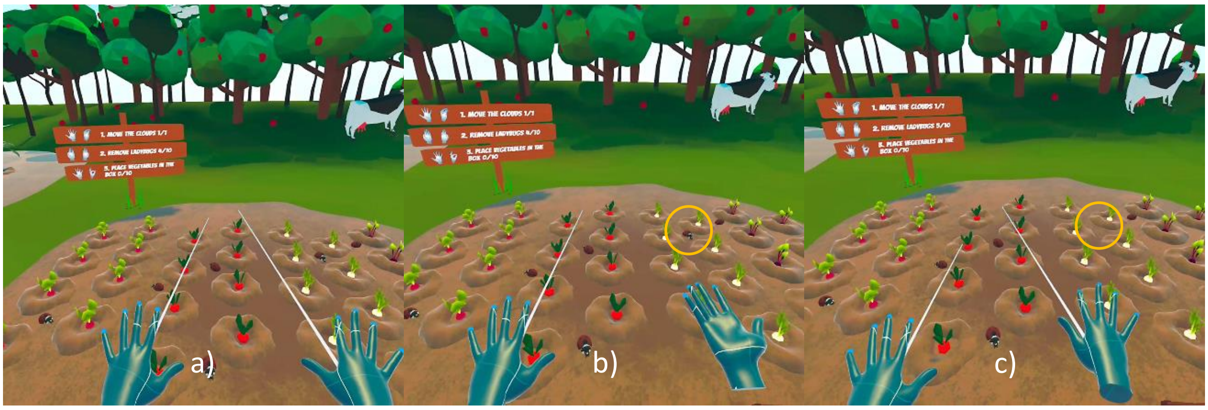



Figure 5-12. Pronation and supination movement to remove the ladybugs: a) Before starting the movement; b) pronation to begin; c) supination to finalise with one ladybug disappearing.

The supination and pronation interaction was implemented following the same reasoning as the flexion and extension interaction. The axis checked in this interaction is horizontal (axis forward.x).

## 5.6 BOARDS WITH IMAGES AND TEXT INDICATIONS

Before the initial testing game started, it was demonstrated to the participants what moves they would have to make. Despite this, it was observed that they forgot very easily the gestures to perform. So, images of the motions and guiding text stating which tasks should be made were introduced and seen as important additions. The images of the gestures/movements and the text guiding the tasks can be seen in Figure 5-13. The boards also show the status of completion of each task.

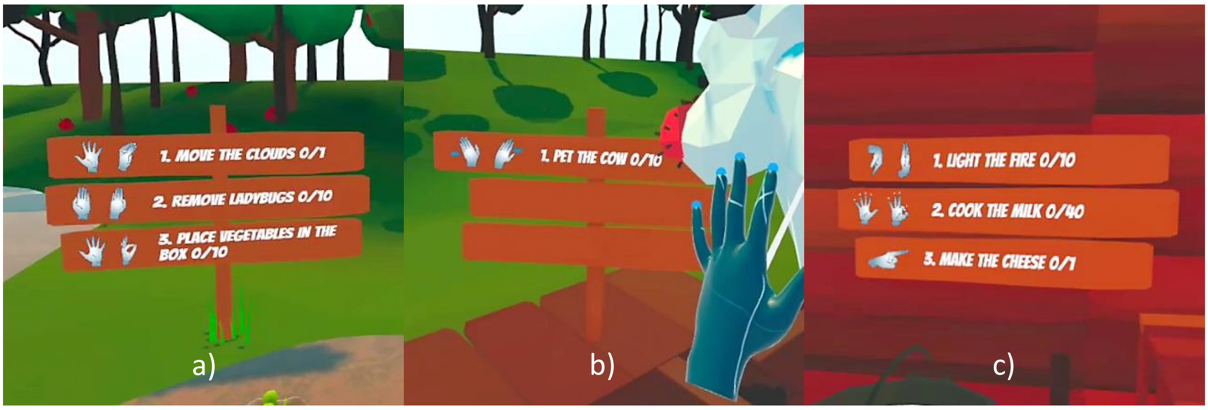



Figure 5-13. Images of the gestures/movements and guiding text for completing the task in the a) crops section; b) cow section and c) cheese section.

## 5.7 TELEPORTATION

The StableHand VR game was set in an open environment where the player could walk freely. Because in the real world there are space limitations, the possibility to teleport from station to station was created. Figure 5-14 presents the phases of the teleportation.

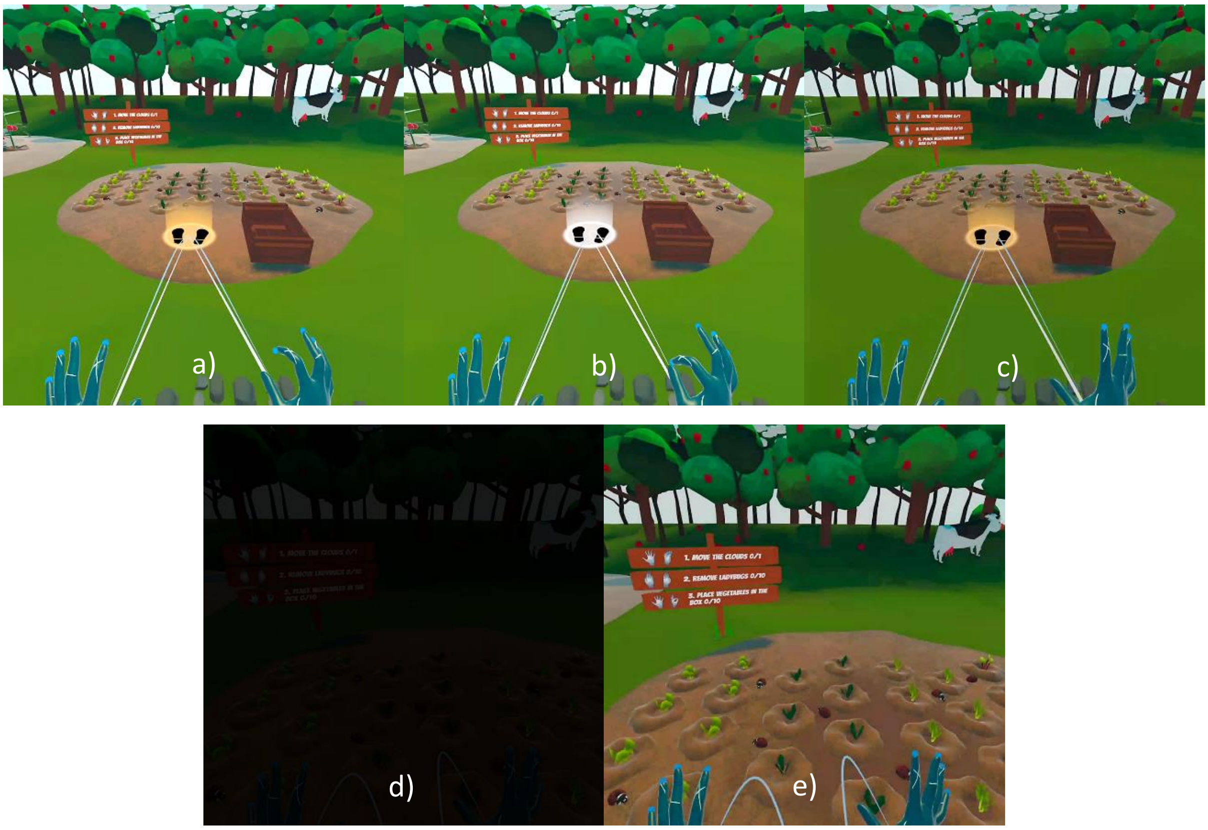



Figure 5-14. Phases of teleportation by Far-Field Interaction: a) footprint and hand raycast interaction; b) station selection; c) scene fade out begins; d) camera position changes and e) scene fade in.

The teleportation was implemented through a far-field interaction to prevent players from suffering from motion sickness. A simple solution to solve this problem was to darken the scene before the teleportation and lighten the scene after. This can also be called as Fading out and Fading in, respectively.

First, the player must direct the white ray from one of his hands to the footprint on the station's ground where he wants to teleport. A cylinder will glow around the footprint once the white ray intersects them, as shown in Figure 5-14a. The player must pinch with the hand's beam intersecting the footprint to select the station, as presented in Figure 5-14b. In Figure 5-14c the player stops pinching, and the fading out process begins. The screen will darken, as shown in Figure 5-14d, the position of the camera will change to the place of the selected footprints, and finally, the scene will fade in again as is possible to see in Figure 5-14e.

## 5.8 EXIT GAME

Finally, an Exit button was implemented to leave the game and return to the Oculus Quest Home Scene. The Exit button is shown in Figure 5-15, and the game is placed in the middle of the three Sections. The player needs to teleport to the middle section and push the button to leave the game.


Figure 5-15. Exit game button.

When starting the game, the player is placed in the middle station. One participant felt difficulties knowing his position and how to teleport during the game validation. A circle of stones was placed around the middle section’s footprints to tackle this problem. These stones can help the player to have a better notion of his position and serve as a reference for the health professional when guiding the patient. For example, the health professional can ask the participant if he sees a circle of stones around him and in this way know if the patient already teleported or not.

## 5.9 MAIN MENU

The menu is normally the first thing a player sees in a game. A common use of menus is to provide convenient access to various operations. In the StableHand VR game, the menu was first created to allow the player to start or exit the game and introduce the game’s atmosphere. The Main Menu went through several changes, and different sections were added along the game’s development. The menu’s final version contains three sections: the main menu, the tutorial, and the multi-language menu. The main menu is presented in Figure 5-16

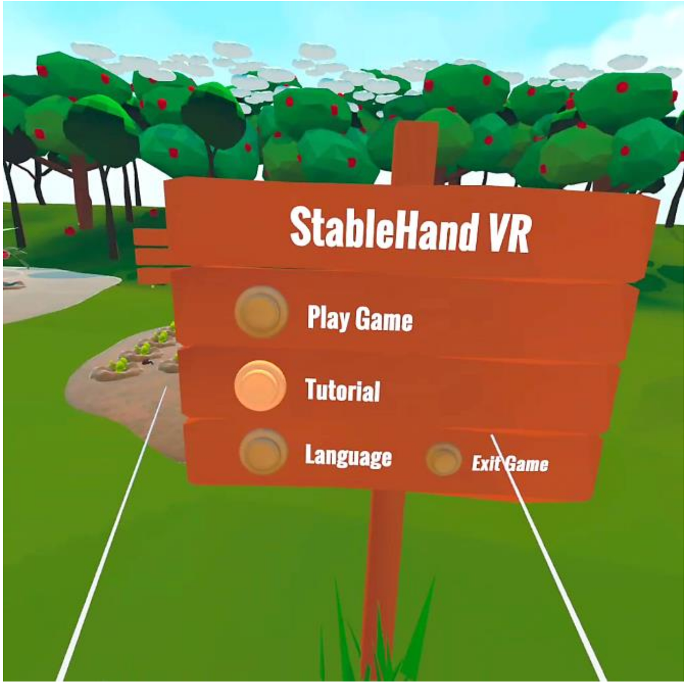



Figure 5-16. Main menu with interaction buttons.

The main menu allows the player to change to the actual game scene by pushing the Play Game button. To go to the Tutorial where the player can learn and practice the gesture to interact with the game objects, the player needs to push the Tutorial button. By pressing the Language button, the player can change the game language. Finally, the Exit Game button closes the application and returns the player to the Oculus Quest Home Scene.

## 5.10 TUTORIAL

The game tutorial was developed after being suggested by the participants in the game's first validation. Participants mentioned that an introductory video explaining the game mechanics and gestures would be a good addition at the beginning of the game. The tutorial was introduced to teach players the "controllers" of the game, i.e. the movements to interact with the game objects.

Upon starting the application, the player is presented with the Tutorial scene. The tutorial is not mandatory, and for starting it, the player only needs to push the start button showed in Figure 5-17. The player can also change between scenes to change the language or go to the Main Menu.

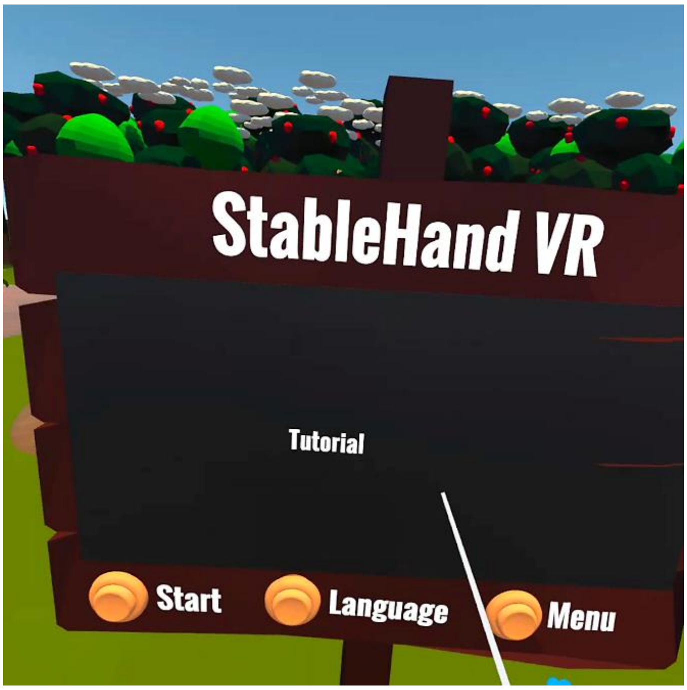



Figure 5-17. Tutorial scene with interaction buttons below.

Upon starting the Tutorial, instructions, and images of the gestures to be made will appear on the screen, as displayed in Figure 5-18a. The player must follow the instructions and replicate the gesture to pass to the following gesture demonstration until it is considered completed. The task's completion is evaluated by achieving the minimum thresholds for the pinch, pinch grip, and sequential pinch gestures and achieving the minimum translation degrees for the pronation and supination, flexion and extension and ulnar and radial deviation gestures. In the end, a message of completion appears on the black screen, as seen in Figure 5-18b.


Figure 5-18. Initial and final stages of the tutorial: a) first instructions after pushing the Start button; b) message of completion after finishing the tutorial.

## 5.11 MULTI-LANGUAGE MENU

The language menu scene was also introduced in the fourth phase of the Project Development Phases, after being suggested by participants on the first validation tests. The multi-language support was implemented using Unity's System.IO and System.Xml packages. A class was created in C# to set a path to an XML file, where the text in the different languages would be stored, and to swap languages. A controller class was also created to set the initial language to English and not destroy this setting when changing between scenes.

The interactive menu to change the language is presented in Figure 5-19 in the different languages introduced. Possible languages of alteration are English, German and Portuguese.


Figure 5-19. Interactive language menu to change between the languages: a) English; b) German and c) Portuguese.

# 6 RESULTS

Two mid-term validations of StableHand VR were performed to test the game's viability and adjust its development. The first validation was performed in able-bodied participants and the second with health professionals working in the rehabilitation field. A final validation to test the game's usefulness, evaluate recorded database parameters and participants evolution over time could not be added to this dissertation due to time restraints.

## 6.1 FIRST VALIDATION

The first validation of the game was performed with eight healthy participants who underwent a ten-minute guided functional task practice followed by a Semi-Structured Interview [91] (Appendix C – Semi-Structured Interview). The guided functional task practice was done with two interactions from the Crops section after independently starting the game. In Figure 6-1 is possible to see three participants trying the game. The interview audio-recordings were transcribed, and content was evaluated, focusing on a detailed analysis of participants' answers. The content was interpreted with the specific purpose of identifying usability problems and to summarizing suggestions for improvement.

Figure 6-1. Participants trying StableHand VR game.

The Semi-Structured Interview was also used to collect preliminary data regarding the player's game's perspectives and the Oculus Quest as the platform for the game's delivery. The questions covered the participants' familiarity with videogames, playing videogames, and the participants' opinion about the Oculus Quest and its hand tracking system, as well as the

StableHand VR game. Ten questions from the System Usability Scale (SUS) were also included in the interview, followed by demographic questions. The SUS is a quick and reliable tool for measuring the usability of various products and services, including hardware, software, mobile devices, website, and applications. It has become an industry-standard having references over 1300 articles and publications [92].

Eight participants (four females, four males), with a mean age of 28 years (range = 22-35 years) used and tested a fully functional element of the StableHand VR game. Participants' demographic data are presented in Table 6-1.

Table 6-1. Participants Demographic Data

| **Participant** | **Demographic Data** | | |
|---|---|---|---|
| | Age | Gender | Pathologies related to the hand |
| **1** | 34 | Female | Previous Fracture; Left wrist ganglion in metacarpus |
| **2** | 31 | Male | No |
| **3** | 27 | Female | No |
| **4** | 25 | Female | Previous fracture |
| **5** | 22 | Female | No |
| **6** | 24 | Male | Previous fracture |
| **7** | 27 | Male | No |
| **8** | 35 | Male | Epiphyseal plate |

Five of the study participants stated they had high experience playing video games, while the other three considered themselves low-experience players. Four participants experienced playing videogames primarily through commercial consoles and three participants through the computer. Before the study was conducted, 75% of the participants had experienced VR, and 25% had not.

Content analysis of the interview transcripts revealed three categories: hardware usability (i.e. Oculus Quest Head-Mounted Headset), software usability (i.e. key configuration and game settings), and suggestions for improvement. The scale used to classify the categories was an altered Likert scale ranging from 0 to 5.

**Hardware usability** of the Oculus Quest was evaluated by each participant compared to other VR devices on the market that the participants experienced before the study. On a scale from zero to five, being zero the Oculus Quest worse than other devices, and five the

Oculus Quest being better than the other devices, it scored an average of 4.2. The device scored an average of 4.3 regarding its easiness of use and an average of 4.1 for comfort.

The participants mentioned positive aspects such as the immersion, the freedom of movements, the graphics, the possibility of adjusting the lenses or the headpiece and using their hands. Six participants referred to the headpiece's weight as a negative aspect of the Oculus Quest and one of the participants noticed some motion sickness after the test.

The sensitivity in capturing the hands' position and movements was referred to as a positive aspect of the device. All the participants stated they felt the virtual hands were their own hands. However, one participant mentioned the tendency to keep her hands closer to her body, which hinders the hand tracking process.

**Software usability** was evaluated in terms of game appeal and how the implemented gestures fit the game tasks. Participants scored game appeal with an average of 4.4 and highlighted the environment, music, sound effects, graphics, and design as positive game aspects. The game was viewed as relaxing and easy to handle.

The movement to interact with the clouds scored an average of 4.3 with a remark from all the participants that the movement was not intuitive at first but became easier once they knew how to make it. The movement to interact with the vegetables scored an average of 4.4. Seven participants noticed that this movement was more intuitive and easier to understand.

**Suggestions for improvement** made by the participants amount to: provide an introductory video explaining the game mechanics and gestures, change the position of the vegetables so the player would not need to pick them directly from the ground, add more challenge, add more movements and alter the size and position of some objects on the background.

Lastly, all participants noted that the StableHand VR game and the Oculus Quest Headset were a good combination and that they would want to use the system in a hand rehabilitation situation. Results obtained for the ten SUS questions are presented in Figure 6-2.

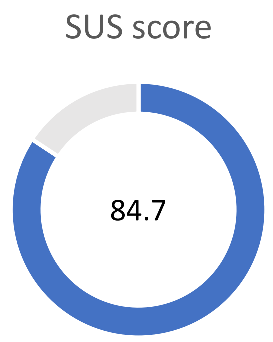



Figure 6-2. SUS score from able-bodied participants' tests.

## 6.2 SECOND VALIDATION

The second validation of the game was performed with four health professionals who underwent a ten-minute guided functional task practice, followed by an online questionnaire (Appendix D – Physiotherapists Questionnaire).

The guided functional task practise was also done with two interactions from the Crops section after independently starting the game. The other interactions and gestures to be implemented were also explained to the participants. The questionnaires' content was evaluated, focusing on a detailed analysis of the health professionals' answers.

The answers were interpreted with the specific purpose of identifying content and usability problems, collect preliminary data regarding the player's perspectives of the game and the Oculus Ques, and to summarize suggestions for improvement. The questions mainly covered the participants' opinion about the Oculus Quest and its hand tracking system and the StableHand VR game. Ten questions from the SUS were also included in the questionnaire, followed by demographic questions.

Four health professionals (two females, two males), with a mean age of 49.5 years (range = 44-54 years) used and tested a fully functional element of the StableHand VR game. Only one participant had a hand-related pathology and went through physiotherapy sessions (six sessions to be precise). Health professionals' demographic data are presented in Table 6-2.

Table 6-2. Health professionals Demographic Data

| Participant | Demographic Data | | | |
|---|---|---|---|---|
| | Age | Gender | Profession | Pathologies related to the hand |
| **1** | 51 | Male | Sport scientist and physiotherapist | Finger fracture (D5[a], middle phalanx), left hand |
| **2** | 54 | Male | Sports scientist | No |
| **3** | 49 | Female | Physiotherapist | No |
| **4** | 44 | Female | Physical therapist | No |

a: Pinkie finger

Content analysis of the questionnaire answers followed the same three categories as those identified in the First Validation. The scale used to classify the categories was an altered Likert scale ranging from 0 to 5.

Three of the study participants stated they had experience playing video games, but two considered themselves very low experience players.

**Hardware usability** of the Oculus Quest was evaluated by each participant compared to other VR devices on the market that the participants experienced before the study. Before the study was conducted, two of the participants had experienced VR: one in a virtual stadium simulation and another in a rehabilitation scenario. The participants did not remember which VR device they used but classified that system as slightly better or equal to the Oculus Quest device. On a scale from zero to five, being zero the Oculus Quest worse than other devices, and five the Oculus Quest being better than the other devices, it scored an average of 2.5. The device scored an average of 4.3 for comfort and an average of 3.0 regarding its easiness of use. One health professional stated that seeing the movements would help and another had some compatibility problems with their glasses.

The hands' graphics were referred to as a "very impressive" aspect of the device, but sometimes the participants experienced short lags in the hands' rendering. To the question "*Did you feel that the virtual hands were your own hands?*" participants classified this feeling with an average of 2.3. One of the participants had several problems understanding the gestures/movements to perform and gave a classification of 0 in this question. However, the participants classified the hand tracking accuracy of the Oculus Quest with an average of 3.8.

**Software usability** was evaluated in terms of game appeal and how the implemented gestures fit the game tasks. Participants scored game appeal with an average of 4.0.

The movement to interact with the clouds scored an average of 3.0 with two health professionals' observations. The first observation was that at the beginning, there was the need to find the correct position to perform the movement and the second that the movement became easier once they knew how to make it. The movement to interact with the vegetables scored an average of 4.0. The health professionals also gave an average of 4.0 for their willingness to advise their patients to use this game as a complement to their rehabilitation. When asked if they thought the patients would be willing to use the game in their rehabilitation, the health professionals gave an average of 3.3.

Other movements (Pronation/Supination, Flexion/Extension, Sequential Pinch, and Radial/Ulnar Deviation) and their interaction with game objects were explained to the health professionals as possible movements to be implemented in the game. When asked if they thought these movements were relevant, they scored an average of 5.0. The small fist (only flexion in the proximal phalanx joint and distal phalanx joint) was suggested to be added.

Positive aspects of the game identified by the participants are the "everyday situations in the game" and the individual movements and the tasks that were considered very good and a very good match. A negative aspect mentioned was the possibility of the game becoming boring after a few sessions.

**Suggestions for improvement** made by the health professionals' amount to provide further situations for hand movements, increased difficulty in the form of a next level, the introduction of instructions for each activity before each exercise, and the implementation of other languages other than English.

Lastly, the participants classified the combination of the StableHand VR game with the Oculus Quest with an average of 4.3. An average of 4.0 was obtained regarding the health professionals' willingness to use the system in a hand rehabilitation situation.

Results obtained for the ten SUS questions are presented in Figure 6-3.

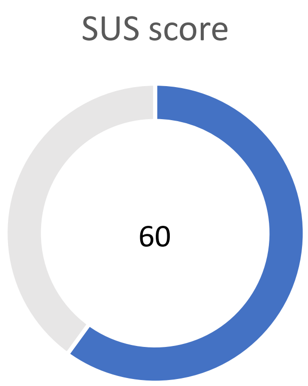



Figure 6-3. SUS score from health professionals' tests.

# 7 DISCUSSION

In the **first validation,** the hardware results were very positive, even though some negative aspects were mentioned by the participants, such as the device's weight and slight motion sickness. The device's weight may be higher than that of other VR devices due to the built-in cameras. However, this very fact is an advantage over other VR systems that require additional external cameras and thus, extra space.

On the other hand, the **second validation** did not present results as promising as those achieved in the first validation. However, the hands graphics and the immersion were mentioned by the health professionals as positive and entertaining aspects that could motivate patients.

Both in the first validation, with the able-bodied patients, and in the second validation, with the health professionals, the participants demonstrated difficulties in performing the gestures at first attempt. They mentioned that seeing the movements would help in the performance.

We believe that the reason behind the difficulties reported by participants to perform gestures correctly at the first attempt might be related to occlusion problems caused by the hands' position while doing the movements. A typical case where this problem occurs is when the hand's back faces the cameras and covers the hands' fingers from the cameras while the participant tries to pinch, this movement would not be recognized. Similarly, if the palm were not directly facing the Oculus cameras, the multi-finger simultaneous pinch would not be recognized. One solution for this problem would be to show the patients the most efficient way to perform the movements and ensure finger recognition.

Hand tracking can exhibit some noise, particularly from lighting, environmental conditions, and complex background (created by various objects or different colours behind the hands). In such cases, hand tracking confidence may become low and even lost completely. Whenever hand tracking is low, the game's virtual representation of the hands fades away to inform the user of the problem and its intensity. However, this solution can be confused with the hands not being at camera range, since there is a tendency to keep the hands and arms close to the body.

The gesture to move the clouds is the same as used in a specific task of hand physiotherapy sessions. This gesture is not common, which was probably the main reason for the participants' difficulty understanding and performing the gesture (in the **first validation**). The health professionals (of the **second validation**) had problems with this gesture because of the need to adjust the hands' position so the Oculus' cameras would recognize them. The pinch gesture is much more common and was easier to understand and perform. A solution to overcome this problem could be introducing a demonstration of the game's gestures, followed by training before the game starts.

The StableHand VR game was viewed as relaxing and easy due to the calm environment, music, and design. The hands' graphics were referred to as a "very impressive" and positive aspects identified are "everyday situations in the game" and the individual movements and the tasks that were considered very good and a very good match. Suggestions for improvements made by the participants highlighted the need to adapt the game for patients with less body mobility since the participants needed to bend down to interact with the vegetables, provide further hand movements, increase the difficulty, introduce instructions for each action, and implement other languages.

SUS scores from both validations were very distinct, positioning the developed system in almost opposing usability ends. Raw SUS scores can be normalized and converted into percentile ranks and grade ranks. Percentile ranks tell how well the raw score achieved compares to others in the database. Grades are closely related to percentile scores and range from A, which indicates superior performance, to F (for failing performance). Table 7-1 shows the percentile ranks, grades, and adjectives for common raw SUS thresholds. The average score (at the 50th percentile) is 68, meaning that a raw SUS above 68 is above average and below 68 is below average. A SUS of 75 corresponds to a 73rd percentile, meaning that the system scored better than 73% of the other products in the database and worse than 27% [93].

Table 7-1. SUS Curved Grading Scale with percentile ranks and grades (adapted) [93].

| Grade | SUS | Percentile Range | Adjective |
|---|---|---|---|
| **A+** | 84.1 - 100 | 96 - 100 | Best imaginable |
| **A** | 80.8 - 84.0 | 90 - 95 | Excellent |
| **A-** | 78.9 - 80.7 | 85 - 89 | |
| **B+** | 77.2 - 78.8 | 80 - 84 | |
| **B** | 74.1 - 77.1 | 70 - 79 | |
| **B-** | 72.6 - 74.0 | 65 - 69 | |
| **C+** | 71.1 - 72.5 | 60 - 64 | Good |
| **C** | 65.0 - 71.0 | 41 - 59 | |

Table 7-2. (continued).

| Grade | SUS | Percentile Range | Adjective |
|---|---|---|---|
| **C-** | 62.7 - 64.9 | 35 - 40 | |
| **D** | 51.7 - 62.6 | 15 - 34 | OK |
| **F** | 25.1 - 51.6 | 0 - 2 | Poor |
| **F** | 0 - 25 | 0 - 1.9 | Worst Imaginable |

In the **first validation,** the SUS average score of 84.7 positioned the proposed system above average in usability and learnability. The letter grade A+ is equivalent to an Adjective Rating of Best imaginable. Six of the participants experienced VR before playing the StableHand VR game and all the participants were young adults. These two characteristics could be reasons for the participants' propensity to classify the system with higher values. All the participants stated they would be very willing to use the game if they need to.

In the **second validation,** the SUS average score of 60 positioned the system below the average. A SUS score of 60 corresponds to the letter grade D, equivalent to an Adjective Rating of OK. The raw SUS of 60 falls approximately at the 30th percentile (scoring worse than 70% of the database's scores). The health professionals, being older and having less experience playing videogames, experienced more difficulties in performing the proposed tasks. These characteristics could be reasons for lower classification values. Even the health professionals stated they would be willing to use the game if they need to and to suggest its use to their patients in a hand rehabilitation situation

The influence of gender in high experience playing videogames and playing StableHand VR has not been assessed due to the small sample size in both validations. It is certainly something that should be tackled with larger groups in the future.

Even with a small sample in both validations, three of the eight able-bodied patients had already experienced fractures and another impairing pathology in the **first validation**. In the **second validation**, one of the four health professionals had experienced a finger fracture. This data shows the propensity of hand/wrist injuries in young and older adults, respectively. Only one of the patients in the **first validation** had physiotherapy sessions after his trauma to the hand. This patient stated he would be very willing to use the game if a new need arose. In the **second validation**, the health professional also had physiotherapy sessions and was willing to use the system if he needed and would also be willing to advise his patients to use StableHand VR as a complement to their rehabilitation.

In the **first validation,** the age range did not cross the 35 years old mark. It is noteworthy that this is not a game for older people, as some might think when discussing rehabilitation, but a gaming solution for younger people and manual workers. The health professionals' age range from the **second validation** was between 44 years and 54 years. Even though the health professionals classified the system with a lower SUS score, they also stated that they would be willing to use the system and suggest it to their patients. These are promising outcomes for StableHand VR's viability and the Oculus Quest to be applied in the rehabilitation context, as it is designed.

## 7.1 LIMITATIONS

The validations performed allowed the identification of some limitations that were addressed throughout the game development. One of them was the recurrent forgetfulness of the gestures to be made in each interaction. This limitation was addressed by demonstrating the gestures, in the form of a tutorial, and adding a reminder of each gesture and interaction to perform in each game section, through hand images and text in the boards. The multi-language option was also added.

Limitations connected to the device, such as the correct way to position the hands for the movement to be recognized by the Oculus' cameras can only be overcome by teaching these positions and reminding players of these characteristics.

The movements Pronation/Supination, Flexion/Extension, Sequential Pinch, and Radial/Ulnar Deviation and their interaction with game objects were explained to the health professionals as possible movements to be implemented in the game. They were considered as very relevant and added to the game.

Gestures such as the small fist (only flexion in the proximal phalanx joint and distal phalanx joint), making a tabletop with fingers, bending and straitening the end and middle joints of the fingers, making a full fist and spreading fingers wide apart and bringing them together were suggested to be added. These gestures were not implemented due to some constraints in identifying the bone positions and defining a viable and simple way to recognize each gesture.

# 8 CONCLUSIONS

## 8.1 CONCLUSION

This work presented the conceptualization and implementation details of StableHand VR, a Virtual Reality game, to improve hand rehabilitation therapy sessions.

Two validations were performed by able-bodied participants and health professionals through ten minutes guided functional task practices followed by a Semi-Structured Interview or an online questionnaire, respectively. The tasks performed focused on two-game interactions made with two distinctive gestures: the pinch and pinch grip. The poke gesture was also implemented but was not evaluated because it could be made with any finger, with the hand extended, and was only used for starting the game.

The questions made in the interview focused on the participants' familiarity with videogames, their opinion about the Oculus Quest, its hand tracking system and the StableHand VR game. SUS questions were made to the participants, followed by demographic questions.

Interviews' transcripts analysis revealed several positive aspects of StableHand VR and Oculus Quest, chiefly among them the easiness of use and engaging experience. The VR game was considered very appealing and relaxing while the Oculus Quest was viewed as providing good graphics, freedom of movement and immersivity.

The SUS scores obtained, and the participants' positive feedback showed the potential of both conceptual and technological approaches adopted for this game to be viewed as a viable complement to conventional hand rehabilitation.

## 8.2 PROSPECT FOR FUTURE WORK

Looking at the results obtained, although promising, there is still a lot to be improved and optimized. Interesting topics for future work involve the general optimisation of the prototype with the introduction of incentives for high-frequency participation in the form of awards or achievements, the possibility of progression in the game, and other game tasks to be performed by players.

Offering game progression, achievements and awards are good motivation elements for the player to spend more time playing the game and exercising. The more time the patient spends playing the game, the highest score he receives from his work, having a positive impact on their treatment and their lives.

New tasks of interactions could be performed with the gestures that the health professionals suggested and the gestures from the six-pack hand exercise program that were not implemented due to the limitations previously presented. Implementing these gestures with viable thresholds is an important step for future work in StableHand VR.

Several issues pertaining to the hands involve acute injuries that cause deformities to the fingers, so the game should also cope with these cases. An approach that could be used by StableHand VR for dealing with hand deformities is allowing patients to perform alternative movements to finish a specific task, e.g. pointing to an object can be made with the index finger or with the medium finger;

The database implemented can also be improved to monitor and save patients' speed, acceleration, and movement direction for each joint. Provide detailed information about the accuracy of performed gestures and a broad range of movements to help health professionals evaluate patients´ state. Patients should track their progress from each session and see their evolution in the game over time. These relevant evaluation parameters could be displayed at the end of the game or in a new menu section. The health professionals could also have customisable game settings to manipulate the game sessions, tailoring them for the patients' needs.

Finally, the tutorial could train and show players the movements and game interactions and record their maximum range and thresholds that could be then used in the gameplay.

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# APPENDICES

# A – DATABASE TABLES CREATION

```
// Create SessionRegister table
sqlQuery = " CREATE TABLE IF NOT EXISTS SessionRegister (beingDateTime TEXT, endDateTimeTEXT)";

// Create SimultaneousPinch table - moveCloud
sqlQuery = " CREATE TABLE IF NOT EXISTS SimultaneousPinch (idSessionRegister TEXT, hand INTEGER,  timePinch TEXT, timeNoPinch TEXT, successful INTEGER)";

// Create RadialUlnarDeviation table - petCow
sqlQuery = "CREATE TABLE IF NOT EXISTS RadialUlnarDeviation (idSessionRegister TEXT, hand INTEGER,  rangeLeft TEXT, rangeRight TEXT, timeLeft TEXT, timeRight TEXT,  successful INTEGER)";

// Create SinglePinch table - Vegetable_Grabber
sqlQuery = "CREATE TABLE IF NOT EXISTS SinglePinch ( idSessionRegister TEXT, hand INTEGER, threshold TEXT timePinchBegin TEXT, timePinchEnd TEXT, successful INTEGER)";

// Create PronationSupination table – removeInsects
sqlQuery = "CREATE TABLE IF NOT EXISTS PronationSupination (idSessionRegister TEXT, hand INTEGER, range TEXT, timePalmUp TEXT, timePalmDown TEXT, successful INTEGER)";

// Create FlexionExtension table - cookVegetables
sqlQuery = "CREATE TABLE IF NOT EXISTS FlexionExtension (idSessionRegister TEXT, hand INTEGER, rangeUp TEXT, rangeDown TEXT, timeUp TEXT, timeDown TEXT, successful INTEGER)";

// Create SequentialPinch table - cookMilk
sqlQuery = "CREATE TABLE IF NOT EXISTS SequentialPinch (idSessionRegister TEXT, hand INTEGER, timeIndex TEXT, timeMiddle TEXT, timeRing TEXT, timePinky TEXT, successful INTEGER)";
```

# B – DATABASE TABLES POPULATION

```
sqlQuery = "INSERT INTO SequentialPinch VALUES('" + idSessionRegister + "','" + hand + "','" + timeIndex + "','" + timeMiddle + "','" + timeRing + "','" + timePinky + "','" + successful + "')";

sqlQuery = "INSERT INTO FlexionExtension VALUES('" + idSessionRegister + "','" + hand + "','" + rangeUp + "','" + rangeDown + "','" + timeUp + "','" + timeDown + "','" + successful + "')";

sqlQuery = "INSERT INTO RadialUlnarDeviation VALUES('" + idSessionRegister + "','" + hand + "','" + rangeLeft + "','" + rangeRight + "','" + timeLeft + "','" + timeRight + "','" + successful +"')";
```

sqlQuery = "INSERT INTO PronationSupination VALUES('" + idSessionRegister + "','" + hand + "','" + range + "','" + timePalmUp + "','" + timePalmDown + "','" + successful + "')";

sqlQuery = "INSERT INTO SimultaneousPinch VALUES('" + idSessionRegister + "','" + hand + "','" + timePinch + "','" + timeNoPinch + "','" + successful + "')";

sqlQuery = "INSERT INTO SinglePinch VALUES('" + idSessionRegister + "','" + hand + "','" + threshold + "','" + timePinchBegin + "','" + timePinchEnd + "','" + successful + "')";

sqlQuery = "INSERT INTO SessionRegister VALUES('" + beingDateTime + "','" + endDateTime + "')";

# C – SEMI-STRUCTURED INTERVIEW

## StableHand VR: Semi-Structured Interview Protocol

Date:________________________ Time:_______________________ Place:_______________________
Interviewer:_________________________________Interviewee:_________________________________

### Present the interviewer and Summarize the purpose/goals of the study

My name is Margarida and I am doing my Master Thesis in Medical Informatics.
This semi-structured interview is designed to evaluate the game StableHand VR. This is a game developed for the Oculus Quest Head-Mounted Headset. This game is developed for hand rehabilitation and when completed, is meant to be used by people with hand disabilities that would need hand physiotherapy. The purpose of this study is to collect preliminary data regarding the player's perspectives of the game and the Oculus Quest as the platform for the game delivery.

### Discuss informed consent form

The interviewee is entitled to total confidentiality and anonymity. The interviewee has the right not to answer a question if he/she does not wish to. The interviewee has the right to stop the interview at any time without negative consequences.
With this said, do you agree to participate in this semi-structured interview?
Do you agree with the audio recording of this semi-structured interview?

## Overview of the interview procedure

This interview will be a two-way communication. I will ask you some questions and would like you to answer them. You can also ask questions.

The questions asked here will first cover your familiarity with games and playing games. Next, we will talk about the device used (Oculus Quest), the game that you tried before this interview (StableHand VR), the hand tracking system embedded on the Oculus Quest, and 10 questions from the System Usability Scale. In the end, I will ask you some demographic questions

## Warm-up Questions

- Do you have any experience playing games? Can you categorize your experience with a number from 0 to 5? Being 0 no experience and 5 fully experienced.
  - How long have you been playing videogames?
  - There are different types of games, for instance, adventure, platform, and puzzle. What type of games did you play and enjoyed more?
  - What devices did you use and liked more?
  - Do you have a favourite gaming memory?
  - If the interviewee does not have any experience with videogames, ask why.
- Did you ever experience Virtual Reality?
  - What games did you play?
  - What devices did you use?

## Substantive Questions

- Regarding the Oculus Quest Head Mounted Display used to deliver the game,
  - How do you compare it with other devices that you previously used? Can you categorize the comparison with a number from 0 to 5? With 0 being The Oculus Quest worse than other devices, 3 similar to other devices, and 5 better than other devices. Why did you give that classification? **1**

  - Is the device easy to use? Can you categorize the easiness of use with a number from 0 to 5? Being 0 impossible to use and 5 very easy to use. Why did you give that classification?
  - Is the device comfortable? Can you categorize it with a number from 0 to 5? Being 0 not comfortable to use and 5 very comfortable. Why did you give that classification?
  - What positive aspects do you find in the device? For instance, the immersion is good, freedom of movement since it does not need a cable connection or graphics.
  - What negative aspects do you find in the device? For instance, the weight, the graphics, or if it made you nauseous.
- Concerning the game,
  - In the game test that you previously experienced, you could only interact with the Crops section of the game. Here you could do two movements to interact with the game: move the clouds and pick and place the vegetables.
    - Regarding the movement made to move the clouds, do you think it is easy to make? Can you categorize the easiness of use with a number from 0 to 5? Being 0 impossible to use and 5 very easy to use. Why did you give that classification?
    - Regarding the movement made to pick the vegetables, do you think it is easy to make? Can you categorize the easiness of use with a number from 0 to 5? Being 0 impossible to use and 5 very easy to use. Why did you give that classification?
  - Do you think it is appealing? Can you categorize it with a number from 0 to 5? Being 0 not appealing to use and 5 very appealing. Why did you give that classification?
  - Do you think it is complex? Can you categorize it with a number from 0 to 5? Being 0 very simple and 5 very complex. Why did you give that classification?
  - What would you change in the game? For instance, the design, the size of the objects, the position of the objects, make the game not stationary or pick the vegetables with different fingers.

  - Did you find any positive or negative aspects? For instance, the art and the design, the concept of the game, the game being stationary, or the objects in the game (their size, disposition…).
- About the hand tracking,
  - Hand tracking accuracy can be viewed as how fast you can see your virtual hands moving while you move your real hands. Do you think the hand tracking system from Oculus Quest is accurate? Can you categorize the accuracy with a number from 0 to 5? Being 0 not accurate and 5 very accurate. Why did you give that classification?
  - Did you feel that the virtual hands were your own hands? Can you categorize it from 0 to 5? Being 0 not like your hand at all and 5 exactly like your hands.
  - How did you feel making the movement to move the clouds?
  - How did you feel making the movement to pick the vegetables?
- Do you think this system (game and device) is a good combination? Can you categorize the combination with a number from 0 to 5? Being 0 a very bad combination and 5 a very good combination. Why did you give that classification?
- Would you want to use the system if you needed? Can you categorize your willingness to use the system with a number from 0 to 5? Being 0 not willing to use the system and 5 very willing to use it. Why did you give that classification?

- **SUS Questions.** For the following 10 items, I would ask you to score them with one of five responses that range from Strongly Agree to Strongly Disagree. To clarify, in the middle you have Agree, Neutral, and Disagree.

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.

9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

### Demographic Questions

- How old are you?
- What is your gender?
- What is your occupation?
- Do you have or had any pathology related to your hands? If so, which?

### Closing

- Thank the participant.
- Inform the participant what will happen after the interview: (1) transcribe the interview, (2) process the data from other interviews, (3) write about the collected data in my thesis.
- Provide contact information: phone number and email.

## D – PHYSIOTHERAPISTS QUESTIONNAIRE

### StableHand VR Questionnaire

My name is Margarida and I am doing my Master Thesis in Medical Informatics. This questionnaire is designed to evaluate the game StableHand VR. This is a game developed for the Oculus Quest Head Mounted Headset. This game is developed for hand rehabilitation and when completed, is meant to be used by people with hand disabilities that would need hand physiotherapy. The purpose of this study is to collect preliminary data regarding the sport therapists/physiotherapists perspectives of the game and the Oculus Quest as the platform for the game delivery.


## Demographic Questions

1. How old are you?

______________________________________________

2. What is your gender?
   - ◯ Female
   - ◯ Male
   - ◯ Prefer not to say

3. What is your profession?

______________________________________________

4. Do you have or had any pathology related to your hands?
   - ◯ Yes
   - ◯ No

4.1 If yes, which pathologies?

______________________________________________

4.2 If yes, did you had physiotherapy sessions? How many?

______________________________________________

## Substantive Questions

1. Do you have any experience playing videogames?

______________________________________________________________________

2. Did you ever experienced Virtual Reality before you tried StableHand VR?

- ◯ Yes
- ◯ No

2.1 If yes, what games did you play?

______________________________________________________________________

2.2 If yes, what devices did you use? (HTC Vive, Oculus Rift, Oculus Quest, Google Cardboard…)

______________________________________________________________________

2.3 If yes, how do you compare the Oculus Quest device with the one you previously tried?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Oculus Quest worse than other devices | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Oculus Quest better than other devices |

2.3.1 Please specify your answer.

______________________________________________________________________

3. Is the Oculus Quest easy to use?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Impossible to use | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very easy to use |

3.1 Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

4. Is the Oculus Quest comfortable?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Not comfortable | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very comfortable |

4.1 Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

5. Did you find any positive or negative aspects did you find in the Oculus Quest device? For instance: immersion, freedom of movements, graphics, weight, motion sickness,...

______________________________________________________________________

6. Regarding the movement to move the clouds, do you think it is easy to make?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Very hard | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very easy |

6.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

7. Regarding the movement to pick up the vegetables, do you think it is easy to make?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Very hard | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very easy |

7.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

8. Do you think the game is appealing?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Not appealing | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very appealing |

9. What would you change in the game?

______________________________________________________________________

10. Did you find any positive or negative aspects in the game? For instance: the art and the design, the concept of the game,...

______________________________________________________________________

11. Hand tracking accuracy can be viewed as how fast you can see your virtual hands moving while you move your real hands. Do you think the hand tracking system from Oculus Quest is accurate?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Not accurate | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very accurate |

11.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

12. Did you feel that the virtual hands were your own hands?

0 1 2 3 4 5
Not at all like my hands ◯ ◯ ◯ ◯ ◯ ◯ Exactly like my hands

13. Do you think this system (game and device) is a good combination?

0 1 2 3 4 5
Very bad combination ◯ ◯ ◯ ◯ ◯ ◯ Very good combination

13.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

14. Would you be willing to use the system if you needed?

0 1 2 3 4 5
Not willing to use ◯ ◯ ◯ ◯ ◯ ◯ Very willing to use

14.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

15. Regarding the other movements to interact with the game (Pronation/Supination, Flexion/Extention, Sequential Pinch, and Radial/Ulnar Deviation), do you think they are relevant?

0 1 2 3 4 5
Not relevant ◯ ◯ ◯ ◯ ◯ ◯ Very relevant

15.1. What movements do you think would be important to add or remove?

______________________________________________________________________

16. Would you be willing to advise your patients to use this game as a complement to their rehabilitation?

0 1 2 3 4 5
Not willing ◯ ◯ ◯ ◯ ◯ ◯ Very willing

16.1. Please specify your answer (only if a value between 0 and 3 was selected).

______________________________________________________________________

17. Do you think your patients would be willing to use this game as a complement to their rehabilitation?

| | 0 | 1 | 2 | 3 | 4 | 5 | |
|---|---|---|---|---|---|---|---|
| Not willing | ◯ | ◯ | ◯ | ◯ | ◯ | ◯ | Very willing |

17.1. Please specify your answer (only if a value between 0 and 3 was selected).

___________________________________________________________________________

## System Usability Scale

1. I think that I would like to use this system frequently.
   - ◯ Strongly Agree
   - ◯ Agree
   - ◯ Neutral
   - ◯ Disagree
   - ◯ Strongly Disagree

2. I found the system unnecessarily complex.
   - ◯ Strongly Agree
   - ◯ Agree
   - ◯ Neutral
   - ◯ Disagree
   - ◯ Strongly Disagree

3. I thought the system was easy to use.
   - ◯ Strongly Agree
   - ◯ Agree
   - ◯ Neutral
   - ◯ Disagree
   - ◯ Strongly Disagree

4. I think that I would need the support of a technical person to be able to use this system.
   - ◯ Strongly Agree
   - ◯ Agree
   - ◯ Neutral
   - ◯ Disagree
   - ◯ Strongly Disagree

5. I found the various functions in this system were well integrated.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree

6. I thought there was too much inconsistency in this system.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree

7. I would imagine that most people would learn to use this system very quickly.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree

8. I found the system very cumbersome (awkward or inconvenient) to use.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree

9. I felt very confident using the system.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree

10. I needed to learn a lot of things before I could get going with this system.
   - ◌ Strongly Agree
   - ◌ Agree
   - ◌ Neutral
   - ◌ Disagree
   - ◌ Strongly Disagree