Designing for Adherence: Cozy Gaming in a Virtual Environment for ACL Rehabilitation

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A thesis presented for the degree of Doctor of Philosophy

School of Electronic Engineering

Dublin City University

August 2026

Declaration

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Dedication

All this would not be possible without all the love and support of my family. Thank you to my parents for encouraging me to always go further, being far from all of you is hard, but we always find ways to remain close, los amo!. To my dad Alexandre, who I greatly admire, who I have always considered my role model and who taught me the value of smart work. To my mom Adela, who would hear my complaints and give me advice whenever I needed it, day or night. Thank you for being my safety net!

To my sister Montse, for always giving me a helping hand, these have been the longest periods of time we have been away from each other, but our complicity and friendship will never break, and although I don't say it with words too often, she knows I love her immensely. Thank you to my brother Alex for the laughs, the lifts, and the nonsense. And of course, for all the free medical advice. To my grandmother Delia, who irradiates love like no other and is always proud of me. To my late-grandfather Santiago, the great academic of the family, look! I did it!

To my brand-new husband, Ronan, thank you for keeping me grounded when things felt like too much, for being there for me, and for teaching me how to handle the cold weather. Thank you for exploring the world with me, being my safe space and my best friend. This PhD not only opened my mind, but also gave me the chance to find you.

To my "academic siblings", Sonal and Sanjaya, we started this journey together, and although the end of it has been kind of hectic for all of us, I will always be thankful for sharing it with you.

To my supervisor, Shirley, whose guidance made this work possible. Doing a PhD has always been described as a painful and stressful process, but I enjoyed every step of the way, and I know that big part of that is because of you. Thank you for all the help navigating this path, I could not have asked for a better supervisor!

And above all, I thank God for giving me the strength and resilience that I needed, for giving me opportunities and showing me the right path to follow.

These 4 years have changed my life, I am not the same person that landed in Dublin on a cold January day from the other side of the pond. I have learned so much, and not only in the academic aspect, I feel that I can take on any challenge that comes my way. This process has only made me stronger and made me eager to see what's next.

Acknowledgements

Special thanks to the Research Ireland Centre for Research Training in Digitally-Enhanced Reality (d-real) for funding this work and degree. Being part of this group has been a great experience for which I will always be grateful.

Very special thanks to my supervisor, Shirley Coyle, for all the patience and guidance. I felt very supported by you during these four years. Thank you to my secondary supervisor, Carol O'Sullivan, for her advice and guidance at different points of the project.

I also want to thank Dr. Kieran Moran for his close collaboration on this project, your insights from the sports science field were very valuable as well as all the encouraging words.

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- **Colorado, L. A. M.**, Baberwal, S. S., Gunawardhana, K. S. D., Moran, K., & Coyle, S. (2025, October). Understanding Barriers in Physical Engagement: Prototyping an Exergame for Anterior Cruciate Ligament Rehabilitation. In 2025 IEEE International Workshop on Sport, Technology and Research (STAR) (pp. 162-167). IEEE

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- **Magre, L. A.**, & Coyle, S. (2023, October). Smart garments for immersive home rehabilitation using vr. In Proceedings of the 25th International Conference on Multimodal Interaction (pp. 736-740).

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- Gunawardhana, K. S. D., Fang, Z., McGuinness, G. B., **Colorado, L. A. M.**, Baberwal, S. S., Wani, W. A., ... & Coyle, S. M. (2025). Innovative Self-Powered Sensing: Potential of Fabrigami and Electrospun Nanofiber-Based Triboelectric Nanogenerator for Joint Biomechanics Monitoring. Small, 21(45), e06363.

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Abstract

Anyone that plays sports, either professionally or recreationally, is at risk of suffering a sports-related injury. Anterior Cruciate Ligament (ACL) tears are one of the most common injuries to obtain within team-based sports. This injury can carry long-term consequences and it is important to follow the rehabilitation process in order to increase the chances of a good recovery. This is key not only for sport-performance, but also for day to day activities and to reduce any injury-related pain. Although the importance to follow a home exercise programme (HEP) is broadly explained to patients by their physicians, few of them adhere to it. This work investigates the barriers faced by patients and aims to address the main challenges. The work focuses on the design of a game called *Cosy ACL*, which aims to increase adherence with a home exercise programme by taking cosy gaming elements and Virtual Reality. *Cosy ACL* immerses users in a slow-paced world to explore while at the same time completing their daily rehabilitation exercises. A user-centered design approach was followed to test different features and interactions that could affect adherence of the users. The novelty of a slow-paced and cosy exergame was well received among the participants who tested the game, who also reported feeling excited to continue playing and exercising. This work highlights the potential of novel exergaming approaches which are tailored to different gamer types. Based on the findings, recommendations for the design of exergames are presented in order to address the barriers that patients face with the aim of ensuring long-term adherence with home rehabilitation programmes for improved recovery outcomes.

Chapter 1

Introduction

1.1 Background and Motivation

In Ireland, team-based sports such as Gaelic Football, hurling, soccer, and rugby, just to mention a few, are very popular among people of all ages and levels of sport [1]. The nature of the aforementioned sports require quick reactions from the players, needing to often land abruptly and make sudden changes of direction, predisposing them to Anterior Cruciate Ligament (ACL) injuries [2]. In Irish Amateur Rugby, this injury contributes to players missing about 20 and 30 per cent of training and playing time in male and female athletes respectively [3], if they ever recover enough to go back to play, as only around 55% of athletes return to competitive sports [4]. Lower extremity injuries represent almost 70% of all sports injuries, in which the ACL injury is the most common, with 1 in 12 injury claims in female collegiate athletes playing Gaelic Football [5, 6]. Amateur athletes are also at a higher risk of sustaining an ACL injury during a match by a non-contact mechanism across several sports, in which rugby shows the highest incidence, followed by soccer [7, 8, 9].

The typical course of action to treat this kind of injury is to undergo an ACL Reconstruction (ACLR) surgery, followed by physical rehabilitation. Right after surgery, while in the recovery room, the patient is given a set of exercises to start moving. Physicians will ensure that surgery went well and that the patient is able

to walk and move independently with the help of crutches to limit the weight on the affected knee. In the first two weeks after the surgery the focus is on decreasing swelling and regaining knee extension, then the focus is on knee flexion [10]. This initial therapy is just the start of the recovery journey and not enough to ensure full recovery which can take up from 6 months up to a year [11], making a Home Exercise Programme (HEP) necessary for the patient to reach their goals in terms of movement and pain management [12]. From week 3 to week 6, the patient starts with the HEP recommended by the Physiotherapist and is monitored in the clinic one or two times a week. From week 6 to 4 months after surgery, the HEP and frequency of physiotherapy appointments changes depending on the progress of the patient, but in general, the patient should show more confidence in the use of the knee and be able to jog and run by the end of this phase and be assessed fortnightly or monthly according to each case [10, 13]. From 4 to 6 months after surgery, patients should have a complete Range of Motion (ROM) in the knee and work toward a safe return to sport with a monthly visit to the physiotherapist. From 6 months to 1 year, the patient should be able to return to sports safely, depending on their progress and with the clearance of the physiotherapist [14, 13].

Although patients are informed that the HEP is essential to regain strength, explosiveness and Range of Motion (ROM), around 50-70% neglect to adhere to their programme and therefore are less likely to reach pre-injury levels, which may prevent them from returning to play in fear of putting themselves at risk of re-injury [15, 16]. In addition to the injury, patients also face other barriers during rehabilitation, preventing them from completing their HEP. These barriers can be psychological (high expectations, fear of re-injury, feelings of isolation, lack of motivation), physiological (kinesiophobia and pain level) or situational (access to services) [17][18][19]. This research focuses on increasing the patients' adherence to their HEP after an ACL injury.

Virtual Reality (VR), has the potential to help patients overcome some of these barriers, enhancing the experience of physical rehabilitation. VR is a technology that

immerses the user in a virtual world, creating the illusion of being in a completely different place [20, 21]. However, this technology alone cannot offer a solution to the barriers that prevent patients from completing their exercises, it is necessary to design an experience that will increase adherence to the HEP, such as gamification, to help reduce the barriers that patients go through during the long process of recovery.

Serious Games (SG) are games that are designed with a specific purpose other than entertainment, such as education and training, and rehabilitation. The main idea is to increase adherence and attention in repetitive tasks [22]. A current limitation of serious games in rehabilitation is that generally these games are competitive, requiring the user to accumulate the most amount of points to either defeat others, or defeat a previous personal score. Also, there is still no long-term study showing that adherence to these games is maintained [23]. It is likely that a game only based on points can lose its appeal after some time, given that it can become repetitive. Designing a game with a set of goals that can be achieved over a longer period of time could help avoid this feeling of repetitiveness in the user. By eliminating the inherent competition in games, stress and pressure on the patient doing rehabilitation may be reduced.

Cosy gaming is a recent game trend which has increased in popularity since 2020, exploring gameplays that look to provide a relaxing environment to their players [24]. Generally, these games are not based on competing with others to be the fastest or defeating an enemy, but rather giving space to reflect on what is being done. The characteristics that make a game "cosy" have the potential to help patients overcome their fears towards their exercises and their recovery, increasing adherence in their HEP. This work analyses the game elements that appeal to a specific type of gamer (according to the HEXAD Gamer Type Questionnaire) called Free Spirits, which has often been overlooked when developing games for rehabilitation. To address this gap, this thesis presents the design and development of *Cosy ACL*, a cosy game for ACL rehabilitation, where the player collects resources by doing sets of rehabilitation

exercises to then obtain rewards. The setting is on a relaxed virtual island where they use the resources to make improvements to their house, or unlock new places to explore on the island. This application is designed to be used from week 6 after the surgery, when patients have recovered from the surgery and are able to apply more pressure on their knee and move more confidently than in previous weeks. The initial *Cosy ACL* prototype was developed and tested on 15 participants. Based on the findings from the first study, improvements were made and a follow up study was carried out over an extended period where two participants took the headsets home and tested the application for a period of 2 weeks. This study demonstrated the feasibility of the system in a realistic home setting, as its intended use. Results from both studies demonstrated high levels of adherence and motivation to do the exercises, especially with users that are identified as Free Spirits. This project shows the potential of the use of VR and cosy gaming to increase adherence in home-based exercises for rehabilitation.

1.2 Research Questions

Taking into consideration the background and motivation, the research questions that are to be answered are listed below:

RQ1: Which motion-sensing technology provides the best capabilities to measure parameters that are important for managing the rehabilitation process at home with a VR system?

Explanation: Considering that clinicians have identified important parameters for the assessment of a patient's recovery, and that a VR headset alone cannot measure all of them, we propose the use of wearable sensors or video recording to obtain that data. We need to determine which technology is feasible for home use and that it is accurate enough for the application.

Expected Outcomes:

It is expected that either a set of sensors or video recordings will help in the measurement of parameters such as the knee range of motion and the position of

the joints during exercise in an unsupervised home setting. This is needed by the physician to evaluate whether the patient is doing the repetitions correctly.

Testing and Validation: First, the practical aspects of different sensors will be studied and compared (calibration, ease of use, set up time). Then, the chosen set of sensors will be used to record the movement of the forward lunges exercise. Video recordings will also be used. A comparison of the exercise will be done between the user wearing a VR headset and not wearing it. This comparison will determine not only if the measurements are taken correctly, but also assess if there is any difference in performance while wearing a VR headset.

RQ2: Does Virtual Reality have the potential to enhance adherence with home exercise programmes in people recovering from knee injuries?

Explanation: Evidence in literature suggests that the immersive capabilities of Virtual Reality influences adherence to the rehabilitation programme in a positive way.

Expected Outcomes: It is expected that the VR application addresses certain barriers identified in ACL patients that do not complete their HEPs. This could impact the way the rehabilitation programmes are designed to include immersive technologies such as VR.

Testing and Validation: To test this hypothesis, a user-centered design approach will be used to develop an immersive VR application for the use of physical rehabilitation on patients with ACL injuries, where real users will test and give feedback on the application.

RQ3: Does a cosy game dynamic have the potential to enhance exercise adherence in people recovering from knee injuries that have been identified as Free Spirits?

Explanation: This hypothesis suggests that the low-stress environment in cosy games, and its inherent long-term game-play will influence adherence to the rehabilitation programme in a positive way. Game elements that motivate Free Spirits are also present in these type of games.

Expected Outcomes: It is expected that the VR cosy game will have implications on the motivation of patients in the rehabilitation programme. This could impact the way gamification approaches for rehabilitation programmes are designed.

Testing and Validation: To test this hypothesis, a user-centered design approach will be used to develop a VR application for use in physical rehabilitation in patients with ACL injuries, whereby real users, who have had ACL injuries, will test and give feedback on the application.

1.3 Outline of the Thesis

This thesis outlines the development of a home rehabilitation system using VR and cosy game features, considering the types of immersive technologies that are feasible for home use and centered on the needs of ACL patients to increase adherence to the HEP. The application that was designed in this work aims to increase adherence of patients in any stage of their recovery posterior to the first 6 weeks post-surgery.

Chapter 2 reviews the current immersive technologies available and how they have been used in physical rehabilitation. Also, the HEXAD User Gamer Types are introduced along with a review of the game elements that have been used in rehabilitation games, identifying a gap in gamification research. Then, the cosy game genre is presented and their benefits are discussed. Lastly, the research questions for this project are laid out.

Chapter 3 first reviews and explores the barriers that ACL patients face, and then the design of the system is described. This includes the gamification elements and the game mechanics, storyboards and first prototypes of the exercises to be performed by the users. Following that, the hardware needed is identified and the first iteration of *Cosy ACL* is more thoroughly described. Then in Chapter 4, the user study design is shown, including details of the questionnaires used. This chapter also shows the results of this first study based on the HEXAD User Gamer Types of the participants and their responses to the questionnaire. After testing the first iteration of *Cosy ACL*, feedback was received from the participants and

improvements made for a second iteration.

Chapter 5, shows the user study design for the second iteration, which was longer in duration. The same chapter shows the results obtained from testing this version of CosyACL.

Lastly, Chapter 6 discusses the contributions of this work and the design implications that can improve the impact of gamified rehabilitation applications. This leads to a list of design guidelines for rehabilitation exergames for Free Spirits. Finally, each research question is answered and limitations and future directions are proposed.

Chapter 2

Literature Review

2.1 Stakeholders

This project has identified three main stakeholders: Patients, Physicians, and Researchers.

2.1.1 Patients

The first identified stakeholders are the patients themselves, that will be directly affected by the outputs of this project, given that they will be the end users of the system and gain benefits from using it. In this context, patients with Anterior Cruciate Ligament injuries are the focus of this project, but the same approach could be extended to other types of injury that require a HEP for an extended period of time, and even to encourage exercise in healthy people who struggle to incorporate exercise into their daily lives.

Currently, some research has been done in order to increase adherence by including mental skill training (MST) after the patients' surgery, given that higher psychological stress due to the injury prevents the patients to complete their rehabilitation programme [25, 26, 27]. These studies have found some efficacy in groups of patients under 18 years old [25], and that strategies such as goal setting and positive self-talk are positively correlated to completion of the HEP [26, 27].

These studies conclude that more research is needed, as the results vary depending on the age of the patients, which may indicate that different strategies are needed depending on the demographic of patients.

2.1.2 Physicians

Physicians are the ones in charge of designing the rehabilitation programme for the recovery of a patient's injury, more specifically, physiotherapists and occupational therapists. These health professionals have the necessary knowledge about human biomechanics and the exercises necessary to recover range of motion, mobility, strength, and balance in patients. Unfortunately, given the volume of patients, and the available time, physiotherapists are not able to offer a clinical setting for these exercises for longer than what is established, given that there are 6-8 physiotherapists available per 10.000 people in Ireland [28]. This is why, after some sessions under the supervision of the physician, patients have a HEP that they must follow to continue the treatment they need. As mentioned above, adherence to these HEP is low, causing patients to take longer to recover or to be unable to return to their previous activities at all.

From the perspective of these stakeholders, it would be useful to create a tool that is accurate enough to allow physiotherapists to keep track of what their patients are doing and if they are adhering to their prescribed exercises without having to schedule appointments, saving time and resources for the medical system and improving waiting times [29, 28]. Also, with a system like this, data can be gathered so that the physician evaluates if any change on the HEP should be made, or simply to make sure that their patients comply with it, making a personalised programme easier to achieve [30, 31, 32]. Currently, physicians are open to VR as a tool for rehabilitation, highlighting benefits towards managing fear related to certain movements and also to use in proprioception training [33, 34]. A common concern is the physical space available to patients and how this affects overall safety for the patients.

2.1.3 Researchers

Researchers working on human performance, sports rehabilitation, human-computer interaction (HCI), human behavior, psychology, and virtual reality, can find the design of the system useful for their own research.

This project encompasses different disciplines due to the nature of the application that is being designed. In Figure 2.1 a graphical representation of the interdisciplinary nature of the project is shown. In terms of the technology used, Virtual Reality and the use of wearable sensors is studied in the context of rehabilitation. The hardware used can affect the way patients use the system; if the headset or the wearable sensors are not comfortable to wear users would not use it even though they consider it a good virtual experience. Then, thinking about the usefulness of the application and its design, it is necessary to study how the users will interact with this specific virtual space (Interaction design), taking into account the conditions of the target users. And because physical injuries and their rehabilitation process (ACL injury rehabilitation) are being studied, the causes and processes to reach the desired recovery stage are also considered. The different disciplines mentioned above are all important for the success of this type of application, but they also have to be considered in conjunction with one another.

The main aim of this project is to provide design recommendations based on clinician-informed decisions, user-centered design, and development and testing of prototypes of home rehabilitation systems.

[35]

2.2 Human Factors

The term Human Factors (HF) has been used to describe the process in which the designer takes human characteristics (physical and cognitive), behaviours, strengths, and weaknesses into account when designing a system/product. There are many definitions in the literature that in simple terms refer to ”designing for human use”

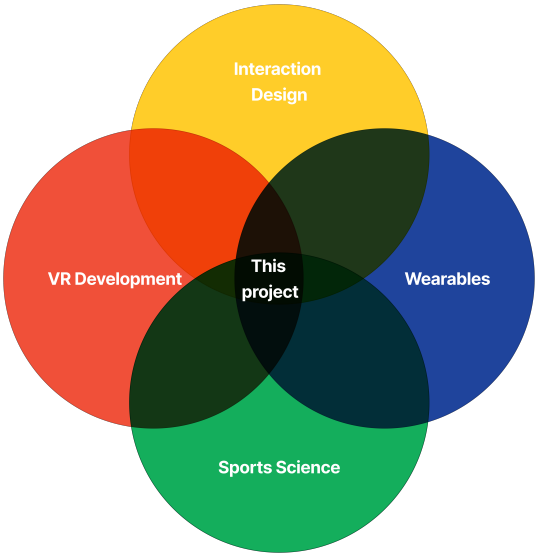


Figure 2.1: Diagram representing the interdisciplinarity of the project.

[36]. Other authors agree that the objectives of Human Factors is to enhance the effectiveness of a system, including safety, efficiency, and well-being of the users [36, 37, 38, 39, 40]. This is why the use of HF could improve support within the injured patient's environment to help them complete their rehabilitation programme. This section defines some of the most common Human Factors that are used to inform the design of the immersive home rehabilitation system.

A number of studies have been carried out in order to understand the barriers that ACL patients face during their rehabilitation process [41, 42]. These barriers are often classified in psychological and physiological factors, service delivery and access, and interaction with others. All these barriers and frustrations could also be classified in terms of human factors as follows:

- Impatience: Impatience on ACL patients appears when their expectations differ from the results they are obtaining. Most of the time patients feel frustrated when they do not achieve good results fast enough.

- Fears: Most ACL patients suffer from kinesiophobia after the injury, this is a fear of certain movements that they believe will cause another injury. Individuals with a greater fear of re-injury are less likely to return to sport. According to Burland et. al [41], up to 24% of athletes do not return to play because of

this. Walker et. al [42] reported that jumping and sudden changes of direction are the hardest movements for patients to overcome this fear. Other types of fear experienced by athletes after an ACLR include the fear of loss of income, having to repeat the rehabilitation programme, and sporting incompetence [41].

- Limited memory: Patients can feel overwhelmed by the amount of information they receive all at once. This can affect their ability to follow the home exercise programme. Also, patients need constant reminders on why they are doing the exercises, and the benefits they will obtain if they remain consistent in their performance [41].

- Changes in need/mood: In various cases, patients feel isolated from people around them, as they do not feel understood by their family and friends. An ACL injury is devastating and career ending for some athletes, and this will also affect their physical stability later in life, with a higher risk of developing arthritis in the knee [43]. These feelings of isolation can affect the overall adherence to finish their exercise programme.

- Needing analogies: As athletes, patients are very passionate about the sport they play. When confronted to a set of repetitive exercises to recover, it can be difficult to see what the advantages are in respect to their specific sport. After being away from the field for at least 6 months, athletes want more specific training, that they can clearly relate to and see that it will help them get back on the game.

- Needing motivation: Boredom is also a big factor in completing physical rehabilitation, given the nature of the programmes. Repetition of a set of exercises is important to build strength back and improving range of motion. For patients, repeating the same exercises everyday is not appealing, and after a few days, they are likely to start skipping the sessions.

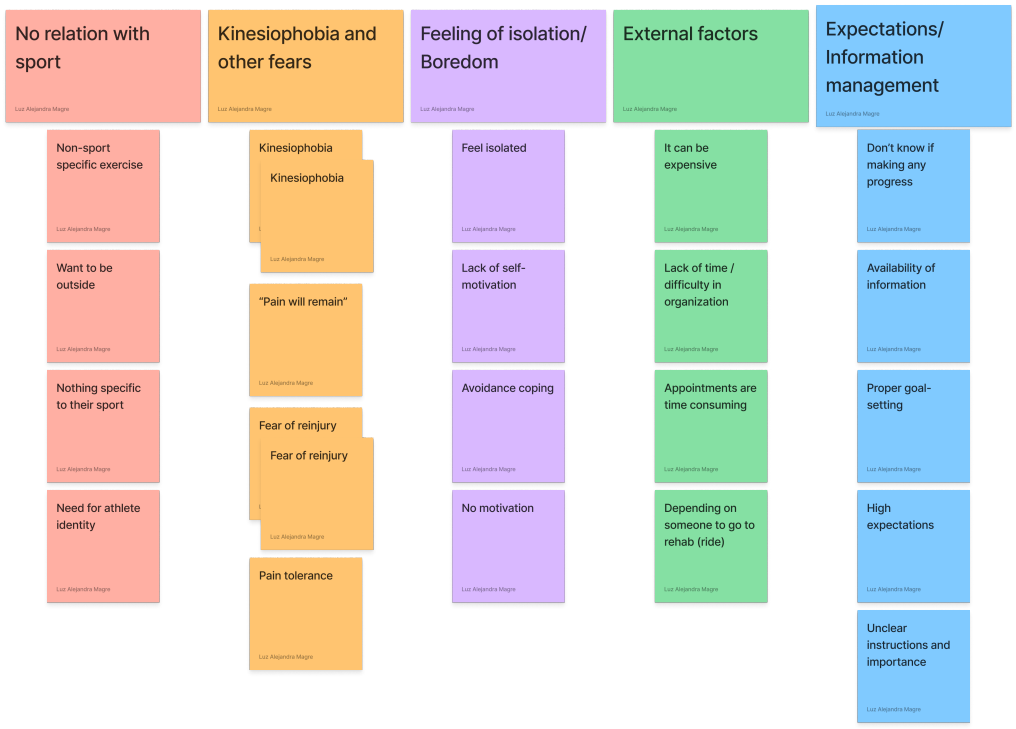


Figure 2.2: Barriers found in literature and grouped in themes.

2.3 Understanding the User

From an initial literature review that was carried out to assess studies that aimed to understand the barriers that patients go through in their rehabilitation process, a number of themes and pain points were identified. Understanding the main barriers will help to design an application that directly tackles the issues that are present for the users.

Four studies related to ACL recovery were carefully selected for review, with the following inclusion criteria: The patients interviewed/studied recovered from an ACL injury, barriers or difficulties for rehabilitation were discussed, studies are peer reviewed publications in English.

From reviewing these studies, the barriers that patients were facing while doing their rehabilitation were noted. From that, these barriers were grouped in similar clusters to be able to define common themes. Figure 2.2 shows the clustering process.

The themes that were identified are the following:

- Kinesiophobia and other fears [44, 45, 42, 41]: "Kinesiophobia", "Pain will remain", "Kinesiophobia", "Fear of reinjury", "Pain tolerance", "Fear of reinjury".

- No relation with sport [45, 44, 42]: "Non-sport specific exercise", "Wants to be outside", "Nothing specific to their sport", "Need for athlete identity".

- Feeling of isolation/Boredom [41, 42, 44, 45]: "Feel isolated", "Lack of self-motivation", "Avoidance coping", "No motivation".

- External factors [42, 44]: "It can be expensive", "Lack of time/Difficulty in organization", "Appointments are time-consuming", "Depending on someone to go to the rehabilitation session (lift)".

- Expectations and information management [41, 42, 44, 45]: "Don't know if they are making any progress", "Availability of information (Too much is overwhelming, too little makes the process confusing)", "Lack of a proper goal setting", "Unrealistic expectations", "Unclear instructions and importance".

2.3.1 Pain Points

According to the previous themes, the following pain points were identified, which can be directly related to the Human Factors defined above:

- Expectations differ from the results → Impatience

- Kinesiophobia and other fears → Fears

- Overwhelming amount of information → Limited Memory

- Feelings of isolation → Changes in Need/Mood

- No relation with their sport → Needing Analogies

- Boredom → Needing Motivation

2.3.2 Personas

From all the themes identified through the research mentioned above, two Personas that would be the target audience for the design of this application have been created. In addition, for these two personas, the characteristics of people with ACL injuries have been taken into consideration. Most patients are young (between 15-30 years old), and more susceptible to sport-related injuries. Half of the injuries that occur are sport-related, and around 70% are non-contact injuries [46]. Even though most patients are male, female athletes have a higher relative risk to an ACL injury, and a higher incidence rate than male athletes [7]. Because of this, a male persona as well as a female persona were created as part of the target audience. It is important to note that basic digital literacy skills are needed for a smooth transition to use immersive technologies such as VR. HMDs in the market are designed to be intuitive to use, but they are also provided with tutorials for beginners. These personas represent the target audience for this application based on the barriers that patients report having during their recovery.

The two personas are Alice (See Figure 2.3) and Jerry (See Figure 2.4).

- **Alice:** Alice is a Sports Science & Health student who also plays soccer and hurling on her university's team. She loves playing sports, feeling active is a big part of her day to day. A year ago, Alice suffered from an ACL injury while playing hurling. She went through the ACL reconstruction surgery and through the physical therapy under clinical supervision. Now she needs to do a home-exercise programme prescribed by her physio, but she is having trouble completing it every day. She either has no time to go to the gym, or she is too afraid to do some exercises. She would like to find a way to complete her exercises, given that it is the only way she can go back to play.

- **Jerry:** Jerry works in IT and loves playing sports regularly, especially tag rugby, participating in tournaments organised by his company. When he was 16 years old, he suffered an ACL injury while playing rugby. Since then,



Figure 2.3: Persona 1. Alice

Jerry has reinjured the same knee twice and received an ACLR surgery each time. He is very familiar with the rehabilitation process, but has trouble being consistent with the home exercises. Because of this, he often has pain not only in his knee, but along the whole leg. This is why Jerry does not play rugby anymore, and has preferred a non-contact sport. Jerry wants something that would make him consistent with the HEP to be able to reduce the pain he is constantly feeling.

This section highlights the importance of human factors in the design of home rehabilitation systems. Five pain points have been identified for ACL patients during their rehabilitation process: Kinesiophobia, No relation with sport, Feelings of isolation/Boredom, Expectations management, and External factors. These pain points directly correlate to human factors that prevent people from performing tasks in a system. Two personas were created to identify the target audience of this rehabilitation system, in which these pain points are also present. By identifying the needs of the intended user, the design of the application is tailored to solve these specific issues, improving the likelihood of adherence to the system, and increasing the frequency to which users do their exercises.

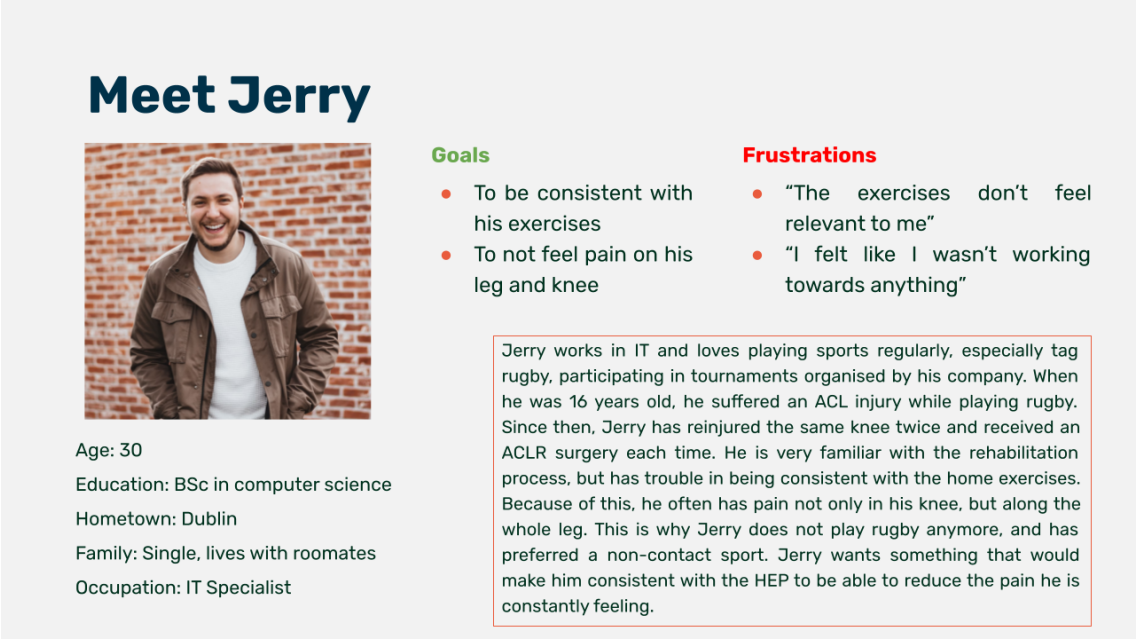


Figure 2.4: Persona 2. Jerry

2.4 Gamification

Gamification is the term that describes adding game elements to a non-game context and turning it into a game activity. This is done to increase adherence and motivation in an activity [47, 48]. The main goal is to create an enjoyable experience for the user in a process that would normally be mundane and uninteresting. In order to do this, game design is key to be able to create gamified experiences, which involves getting to know who is going to use the application and what motivates them to get into the game in the first place.

2.4.1 HEXAD User Gamer Types

Motivation and adherence can vary from person to person; and what motivates a person to do a task could be vastly different from other people. In the same way, some people prefer to play certain types of games over others. For example, some people prefer shooting games, and others prefer playing more casual games.

The gamification user types HEXAD scale [49] is a framework based on user gamer types, dividing users into six categories: Free spirits, Achievers, Philanthropists, Players, Socialisers, and Disruptors. Each of these gamer types has certain

Gamer Type	Description
Free spirits	Motivated mainly by autonomy and self-expression.
Achievers	Motivated by challenges, looking for self-improvement.
Philanthropists	Motivated by purpose and meaning.
Players	Motivated by rewards.
Socialisers	Motivated by connection with others.
Disruptors	Motivated by change.

Table 2.1: Description of the HEXAD gamer types. Based on the work of Tondello et. al. [49].



Figure 2.5: HEXAD gamer types. Based on the work of Tondello et. al. [49].

characteristics of what motivates them in a game. Table 2.1 shows a short description of what motivates each gamer type.

These categories help identify the game design elements that each group finds more appealing and contribute to the long-term adherence of the game. In figure 2.5, you can see a graphical summary of the main user types. The inner hexagon depicts the main motivation of each user type that is in the outer hexagon.

2.4.2 Game Elements in Rehabilitation

In this section, games made for the purpose of rehabilitation are reviewed, identifying the game elements that are in use, and classifying them into a gamer type that the game would appeal to, making it more likely for this type of gamer to keep playing for a longer period of time. The gamification user types HEXAD scale described in Section 2.4.1 will be used. The game elements that will be identified are shown

in Table 2.2, along with the gamer type that they appeal to. It is worth noting that every person is a combination of all the gamer types, but one of them would be dominant and therefore show more preference towards a certain type of game elements.

Gamification using mobile devices

Mobile phones have become a must-have in our daily lives, using them for almost any task when we are on the go. Smartphones have come a long way and nowadays they are an affordable option for applications that require accelerometers, gyroscopes, motion sensors, etc. In this section, research on gamification for rehabilitation using mobile devices such as smartphones or tablets will be discussed.

Augmented Reality (AR) allows to add digital elements to the real environment, and this concept is often used in mobile applications given its portability and ease of use for the users. These capabilities have been used by researchers to add gamification elements to the rehabilitation process. This technology has been used for upper-limb rehabilitation for stroke patients, where specifically designed games have been developed to restore physical and cognitive skills [50, 51, 52]. These articles highlight the low cost of the equipment and its suitability for home use, as well as increased motivation from the patients.

For the lower-body, Garcia et al. [53] developed and presented three AR games targeted at ankle sprain rehabilitation, showing the potential of portable solutions for home-based therapy and how to avoid the use of additional hardware to get the position of the feet. In other cases, such as the work of Chang et al. [54], where the rehabilitation target is the knee, a knee pad with sensors is used to detect the correct movements of the leg.

Depending on the rehabilitation goal, more hardware in addition to the smartphone may be needed to provide the correct interaction to achieve the desired movements, or to collect data for physicians. That is the case in the work of Rahman et al. [55] and Ahmetovic et al. [56], where the mobile phone serves as a screen

HEXAD Player Type	**Game elements**
Philanthropists	- Collection and trading - Gifting - Knowledge sharing - Administrative roles
Achievers	- Challenges - Certificates - Learning new skills - Quests - Levels or progression - Epic challenges (Boss battles)
Players	- Points - Rewards or prizes - Leaderboards - Badges and achievements - Virtual economy - Lotteries or games of chance
Socialisers	- Guilds or teams - Social networks - Social comparison - Social competition - Social discovery
Free Spirits	- Exploratory tasks - Non-linear gameplay - Easter eggs - Unlockable content - Creativity tools - Customisation
Disruptors	- Innovation platforms - Voting mechanisms - Development tools - Anonymity - Anarchic gameplay

Table 2.2: Game design elements that are preferred by each HEXAD Player Type

to visualise the games and therefore the sensors in the device cannot be used to detect movement at the same time. The authors make use of a wearable wristband containing an IMU to detect movement and send the information to the game to pass the levels or accumulate points.

Table 2.3 summarises the games for rehabilitation that use some form of mobile device as their interface. It is noticeable how most of the games rely on points as their main gamification element, suiting the Player gamer type. Only a few of them also included levels or some kind of progression, appealing to the Achievers gamer type, but also, highlighting the importance for the user to see that they are making advancement towards their recovery. In the works described in this section, the authors do not mention other game elements that could fit other gamer types.

Gamification using desktop computer

The Kinect sensor was released by Microsoft in 2010 as a motion sensing input device, aimed to be used with their Xbox game console [57]. This device requires no controllers and can track full-body motion of the user. Being a peripherial and not a gaming console by itself, researchers have used its full-body tracking for applications such as rehabilitation. Herne et al. [58] uses a non-immersive VR setup (Desktop computer) and a Kinect sensor for upper-limb rehabilitation for stroke patients. In the game used, the player has to control the path of a character that is skydiving. The main conclusion of this study claims that to increase adherence, more personalised experiences have to be developed. In the work of Randriambelonoro et al. [59], they developed a system that uses a desktop computer, a Kinect sensor, and ActivLife (rehabilitation equipment to provide stability). Their goal was to gamify the rehabilitation process in older adults with musculoskeletical issues. They found the system to be as effective as the standard treatment, although there was a slight increase in hand grip strength.

By reviewing the literature in this field it was noted that there were fewer games designed to be used in a desktop setting. This may be due to the rehabilitation

Reference	Rehabilitation Goal	Hardware	Game	Game elements	Player type
LaPiana et. al [50]	Stroke rehabilitation (Upper-limbs)	Smartphone, AR Headset, marker on hand	Game about swimming the ocean and feeding turtles	Points	Players
Li et al. [51]	Stroke rehabilitation (Upper-limbs)	Smartphone, fingerless glove	Cognitive serious games	Points	Players
Choi et al. [52]	Stroke rehabilitation (Upper-limbs)	Smartphone, tablet	4 mini-games tailored to elbow and shoulder exercises.	Points	Players
Garcia et al. [53]	Ankle sprain rehabilitation	Smartphone or tablet, marker	Three mini-games tailored to the ankle exercises	Levels or progression	Achievers
Chang et al.	Lower-body rehabilitation	Knee pad with sensors, tablet	Kicking game	Points	Players
Rahman et al. [55]	Frozen shoulder	Smartphone, wearable wristband	Pluck the fruits game (9 exercises)	Levels	Achievers
Ahmetovic et al. [56]	Children with Haemophilia	Smartphone, wearable inertial sensors	Existing mobile games: Super Mario Run, Tap tap dash, Flappy dunk, Jetpack	Points, levels or progression	Players, Achievers

Table 2.3: Summary of Game elements for rehabilitation in Mobile games.

Reference	Rehabilitation Goal	Hardware	Game	Game elements	Player type
Herne et. al [58]	Stroke rehabilitation (Upper-limbs)	Desktop PC, Kinect sensor	Skydiving game	Points	Players
Randriambelonoro et al. [59]	Musculoskeletical rehabilitation in older adults	ActivLife (rehab equipment), Kinect sensor, Desktop PC	Going up stairs game	Points	Players

Table 2.4: Summary of Game elements for rehabilitation in Desktop games.

process requiring constant movement, and a desktop could limit the space available to the user. In the reviewed papers, the main game element used is the accumulation of points in a session, and no description of other gamification elements is apparent in the articles. Table 2.4 shows that both of these works only appeal to the Player gamer type.

Gamification using video game consoles

Videogame consoles have been around since the 70s [60], providing entertainment at the reach of our fingertips. Many game genres and stories have been told through game consoles, but it has also helped to develop new ways of interaction with devices and software. This section describes how these commercially available devices have been used to provide a gamification experience to patients.

Nintendo launched its first Wii console in 2006 [61], innovating with its way of interacting with games. Using motion-tracking controllers, the possibilities of using gestures and movement expanded the range of games that could be designed, the Wii Sports games [62] being one of the most successful ones. In 2017, the Nintendo Switch was released [63], using the motion tracking capabilities of its predecessor, and adding portability. Both of these consoles have been used to increase physical activity for their users. Researchers have also studied their potential in rehabilitation therapies.

Two reviews have provided information on the use of the Nintendo Wii for rehabilitation in stroke patients. The work by Aguiar et. al [64] focuses on motor function rehabilitation and balance using the games included in Wii Sports, Wii Fit [65], and the Cooking Mama [66]. Five studies were collected and analysed, concluding that there is an improvement in motor function, but also that it is unclear whether it is effective for balance training. Later, in the work of Ghazavi et al. [67], by analising 22 studies, concluded that there is an improvement in balance but not in gait speed. Another work by Anwar et al.[68], uses the Nintendo Wii and the same games for stroke rehabilitation in the upper limbs. They tested the games in 68 participants for a period of 6 weeks, they observed improved balance, sensorimotor function, joint range, and less pain of the upper limbs.

In the work of Lima et al. [69, 70], the Nintendo Switch was the chosen tool for rehabilitation in older adults who live in nursing homes, with the goal of improving balance, independence, and cognitive ability. The game used was the Nintendo Switch Sports [71], specifically bowling, badminton, tennis, and volleyball. Their results show therapeutic benefits and high motivation in the participants. Some patients showed difficulties given low technology literacy, and the programme is limited to supervised use to ensure patient safety.

The use of the Nintendo Wii console has also been used for rehabilitation in the lower limbs. Manlapaz et al. [72], used this console for lower-limb balance training in patients with knee ostheoarthritis. The games used were from Wii Fit and they were related to balance to some extent. This study resulted in enjoyment and increased motivation to continue with the training, which led to an improvement in knee muscle strength, balance, and less fear of falling.

Microsoft also released a motion sensor-based console, the Kinect (previously mentioned in Section 2.4.2). For rehabilitation purposes, research has been done around the use of commercially available games within the Xbox interface. For stroke rehabilitation, the Kinect Sports pack and Kinect adventures have been widely used [73, 74, 75, 76]. These studies conclude that there is improvement in overall treat-

ment when added to conventional rehabilitation. All games used rely on Points, Achievements, and Challenges as the game elements to increase motivation. One study in particular focused on supervised group sessions, adding a social competition element, which the patients found motivating [75].

A study by Voon et al. [77] focused on rehabilitation for burn patients, measuring upper-limb function, pain, and kinesiophobia. Using the Kinect Sports pack, there was an increase in physical activity time, and improved motivation, but there was no difference in motor function results and kinesiophobia (Fear of making certain movements). Another limitation discussed by Chanpimol et al. [78] is the age of the patients. In their study, using the same technology and games for Traumatic Brain Injury (TBI) rehabilitation, they show improvement in balance dysfunction, but discuss that commercial games may be more suitable for a younger audience. These studies show that using these type of games would be more widely accessible to the population, but better results could be shown when using games tailored to the patients' needs.

When considering off-the-shelf technology, comparing their features can inform and serve as a guide to finding the most suitable device to use for a specific treatment. Marotta et al. [79] reviewed eight studies to compare the use of the Nintendo Wii and the Xbox Kinect in the rehabilitation of functional locomotion in patients with Parkinson's disease. In general, exergames has benefits for patients, but it is discussed that when the patient suffers from a cognitive disorder, the Nintendo Wii platform is a better device than the Xbox Kinect. A similar conclusion is found in the work of Cheung et al. [80], where a participant with Acquired Brain Injury (ABI) used the Kinect games as part of their rehabilitation, but the researchers had to change to the Nintendo Wii in the last two sessions. The authors observed that the Kinect requires a high level of cognitive and physical functional activity, making it very difficult for patients that lack these abilities when they start their treatment. This highlights the importance of using the right device and game depending on the use case.

As seen in Table 2.5, these applications are based on commercially available games from each console, making it very accessible to users. As these games are not made with rehabilitation in mind, there are no specific exercises for patients with certain injuries and diseases, making it difficult to adjust difficulty to an appropriate level. Also, given that these are commercial games designed towards general fitness, exercise, and sports, the game relies on elements such as points, scoreboards, levels, and visual progression, which appeal only to Players and Achievers gamer types. Only one of these applications makes use of social competition as a way to motivate the patient, making it more attractive to Socialisers, but it is the only game element from this gamer type that was used. As with the previous interfaces, there is no research around designing a rehabilitation game towards attracting Philanthropists, Free Spirits, and Disruptors.

Reference	Rehabilitation Goal	Hardware	Game	Game elements	Player type
Aguiar et. al [64]	Stroke rehabilitation, motor function and balance	Nintendo Wii	Wii Sports, Wii Fit, Cooking Mama	Points, Leaderboards, Levels	Players, Achievers
Ghazavi et al. [67]	Stroke rehabilitation, balance, gait	Nintendo Wii	Wii Sports, Wii Fit, Cooking Mama	Points, Leaderboards, Levels	Players, Achievers
Anwar et al. [68]	Stroke rehabilitation	Nintendo Wii	Wii Sports, Cooking Mama	Points, Leaderboards, Levels	Players, Achievers

Lima et al. [69, 70]	Rehabilitation in older adults	Nintendo Switch	Nintendo Switch Sports	Points, leader-boards, challenges	Players, Achievers
Manlapaz et al. [72]	Knee osteoarthritis (Balance training)	Nintendo Wii	Balance games from Wii Fit: Soccer, Heading, Table Tilt, Penguin Slide, and Ski Slalom	Points, Leader-boards	Players
Park et al. [73]	Stroke rehabilitation	Xbox 360, Kinect, TV	Kinect Sports Pack, Kinect Sports Pack 2 (Mini-games)	Points, leader-boards	Players

Afsar et al. [74]	Stroke rehabilitation	Xbox 360, Kinect, TV	Kinect games: Mouse Mayhem, Traffic Control, Balloon Buster, and Mathercising	Points, leaderboards	Players
Schahama et al. [75]	Stroke rehabilitation	Xbox 360, Kinect, TV	Bowling (Kinect sport), 20000 leaks (Kinect adventures)	Points, challenges, achievements, social competition	Players, Achievers, Socialisers
Turkbey et al. [76]	Stroke rehabilitation (Upper-limbs)	Xbox 360, Kinect, TV	Xbox 360 Kinect games (Bowling, Mouse Mayhem)	Points, challenges, achievements	Players, Achievers
Voon et al. [77]	Burn patients (Upper-limbs)	Xbox One, Kinect, TV	Kinect Sports Pack	Points, challenges, achievements	Players Achievers

Chanpimol et al. [78]	Traumatic Brain Injury rehabilitation	Xbox One, Kinect, TV	Shape Up, Kinect Sports: Rivals	Points, challenges, achievements	Players, Achievers
Marotta et al. [79]	Functional locomotion in Parkinson's disease	Xbox Kinect, Nintendo Wii	Kinect Adventures, Kinect Sports, Wii Fit	Points, leaderboards, challenges	Players, Achievers
Cheung et al. [80]	Acquired Brain Injury rehabilitation	Xbox Kinect, Nintendo Wii	Kinect Adventures, Kinect Sports, Wii Fit	Points, leaderboards, challenges	Players, Achievers

Table 2.5: Summary of Game elements for rehabilitation in video game consoles.

Gamification using virtual reality

Virtual Reality has the potential to improve adherence to the rehabilitation programme, given its capabilities of immersion and interaction. By "transporting" a patient into a different and more encouraging environment, adherence to rehabilitation could be improved, but it is also necessary to take gamification into account to be able to overcome the novelty effect of the VR experience. Rehabilitation for stroke patients using VR and gamification has been studied to determine if it is possible to improve the patients' daily life skills by using task-based mini-games for several situations like pushing a glass, rolling a pin on a countertop, watering plants, cleaning a window, etc [81, 82]. In both studies, patients showed improvement in motor skills, and also manifested enjoyment while using the equipment, even though none of them was familiar with VR until their participation in the study.

The work of Ota et al. [83] explores the use of VR for frozen shoulder rehabilitation by gamifying the table reach exercise. The developed game for this study asks the user to sharpen knives, and depending on how many knives they manage to sharpen, they can access improvements of a virtual city. In this work, they also introduced a scenario in which the user could speak to another user to add a social component. They found that using these game elements, the patients had an increased exercise time, having the potential to improve the recovery of patients because the exercise is done more often and for longer times.

The previous studies focused mainly on upper-limb rehabilitation, but lower-limb rehabilitation in VR can be challenging given that the current technology of HMDs doesn't track the movement of the lower part of the body.

Virtual reality can be accessed not only through a HMD device, but it is also possible to have these experiences through a mobile phone, with specific applications and very simple hardware to hold your phone in front of your eyes like a standalone HMD. This limits the experiences, as there are only 3 Degrees of Freedom (DOF) available, and other hardware may be necessary to track the user's movement. However, some research has been done on the use of these low-cost devices to provide rehabilitation treatment. Hin Man et al. [84] uses a mobile VR headset called Shinecon 5.0 [85] and a motion sensor on the knee for lower-limb strength training, specifically for patients with knee ostheoarthritis. The developed game is task-based, in which patients have to water flowers with the correct movement of the knee. The study found improvements in exercise adherence, but there were difficulties in managing the technology used, especially the motion sensor. Similarly, Ovidio et al. [86] present a puzzle game for stroke patients, intended to be used in the ICU within the first hours after a stroke. The system uses a mobile VR set (Samsung Gear VR [87]) and a motion sensor to track hand movements. Assembling puzzles shortly after the stroke occurs has the potential to improve the recovery of the patients, although this has not been tested on participants yet. While this has the potential to support neuromotor recovery in an innovative way, there is little

consideration given to the game elements used to motivate the patients besides the completion of the puzzles.

Some researchers have included other hardware along with the HMDs to obtain more information that they require for the rehabilitation session. Others use equipment that will help the patient perform the movement or feel more immersed. This is the case in the work of Soares et al. [88], where they use a real bicycle along with the HMD in a racing game in which patients bike for a certain number of laps in a virtual environment while the physician monitors the progress and edits the patient's individual goals. This system is used for lower-limb rehabilitation. The study does not specify what condition or injury the patients had. For upper-limb rehabilitation, Moreira et al. [89] use a Meta Quest 2 and a robotic arm (Kuka LBR Med 7 R800 [90]) for shoulder rehabilitation. The robotic arm serves as a physical element that provides some resistance against the movement that the patient is making. The two games tested are task-based, in order to emulate the Standing Row and the External Rotation exercises.

As with the previous interfaces, Table 2.6 shows a summary of the games that have been used in VR for rehabilitation. Points are still the main gamification element, along with levels or progression. The tendency that can be seen with this technology is that researchers have not used pre-designed games for their studies. Instead, they have designed the games or mini-games according to the injury or condition they were studying. Making use of this immersive experiences allows the user to perform more natural movements, giving an opportunity to simulate activities of daily life in the games. As for the gamer types, the majority of them still appealing only to Players and Achievers. Only one of the reviewed papers (Ota et al. [83]) made use of more gamification elements, such as rewards and virtual economy (for the Player gamer type), and social comparison (for the Socialiser gamer type).

Table 2.7 summarises and visually shows which gamer types are being targeted in the studies that were reviewed. Almost all of the studies rely on Points as the

Reference	Rehabilitation Goal	Hardware	Game	Game elements	Player type
Fregna et al. [82]	Stroke rehabilitation (Upper-limbs)	HMD (Meta Quest 2)	Four task-based mini-games	Levels	Achievers
Liu et al. [81]	Stroke rehabilitation (Upper-limbs)	HMD (Not specified)	16 task-based mini-games	Points, levels	Players, achievers
Hin Man et al. [84]	Lower-limb strength training	Mobile VR (Shinecon), Motion sensor	Perform exercises to water plants	Points, levels	Players, Achievers
Ota et al. [83]	Frozen shoulder rehabilitation	HMD (HTC Vive), Vive trackers	Knife sharpening game	Points, rewards, virtual economy, progression, social comparison	Players, achievers, Socialisers
Ovidio et al. [86]	Stroke rehabilitation	Mobile VR (Gear VR), biomechanics sensor node (BSN)	Assembling puzzles	Levels	Achievers
Soares et al. [88]	Lower-limb rehabilitation	HMD, bicycle, desktop computer	Laps around a virtual environment	Points, badges, individual leaderboard	Players
Moreira et al. [89]	Shoulder rehabilitation	HMD (Meta Quest 2, Robotic arm (Kuka LBR Med 7 R800)	Game 1: Sawing game, Game 2: Pulling lever to elevate a hot air balloon	Points	Players

Table 2.6: Summary of Game elements for rehabilitation in Virtual Reality.

main gamification element, closely followed by the use of Levels. This shows that the games included in this review, target mainly Player and Achiever gamer types. Only two studies included a social element to their games, which used Social Competition and Social Comparison to motivate the users to improve in their exercises. The topics and types of exercises vary between all the studies, but the gamification elements are almost the same. There were no other game elements in the previous studies that pointed to other gamer types. There is a clear gap in game design in rehabilitation for the remaining gamer types (Philanthropist, Free Spirit, Disruptor).

As stated by Tondello et al. [91], the most common user types are 'Philanthropist', 'Free Spirit', and 'Achiever', and the least common one is 'Disruptor'. As seen in this review, most games for rehabilitation would appeal to the 'Player' gamer type, followed by games for the 'Achiever' gamer type, but none of them contain game elements that appeal to the 'Philanthropist' and 'Free Spirit' gamer types. This seems contradictory when the results of all of these studies are positive in adding gamification to the rehabilitation process. According to Marczewski [92], this is due to the fact that initially, most users that come into a gamified system, are motivated at that point by the rewards (Points), but if the design of the system does not include elements for the user's gamer type, users may lose interest in the system after the novelty of it passes. Ideally, a gamified system should be designed with the gamer types in mind, with a reward path along the way of the game to ensure initial and long-term adherence [92].

As per the current research in gamified rehabilitation systems, there is still a need to add elements that appeal to Philanthropists and Free Spirits, given that they are a very common gamer type in the general population. For this project, the focus will be on a gamified rehabilitation system that appeals to Free Spirits.

2.4.3 General Game Design Elements for Gamification

Independently of the gamer user type, some game design elements help to keep players motivated in the on-boarding process and that initial stage when they are

	Philanthropist	Achiever	Socialiser	Player	Free Spirit	Disruptor
LaPiana et al.						
Li et al.						
Choi et al.						
Garcia et al.						
Chang et al.						
Rahman et al.						
Ahmetovic et al.						
Herne et al.						
Randriambelonoro et al.						
Aguiar et al.						
Ghazavi et al.						
Anwar et al.						
Lima et al.						
Manlapaz et al.						
Park et al.						
Afsar et al.						
Schahama et al.						
Turkbey et al.						
Voon et al.						
Chanpimol et al.						
Marotta et al.						
Cheung et al.						
Fregna et al.						
Liu et al.						
Hin Man et al.						
Ota et al.						
Ovidio et al.						
Soares et al.						
Moreira et al.						

Table 2.7: Summary of gamer types available in rehabilitation games.

getting to know the game mechanics and the story. These are common elements that make a game playable for the user. This does not mean that all of these elements need to be present, but if the narrative and the game mechanics allow it, they will provide a better experience. This is based on the work by Marczewski [92] and Tondello et al. [49].

- On-boarding/Tutorials/Signposting: Normally, users do not read manuals before starting to play, so it is a good practice that when initiating the game, there is an on-boarding process to teach the player how to play. After that, signposting can help the users when they are stuck on the next step to follow. These elements are all about guidance.

- Progress/Feedback: All gamer types need a way to measure progress in the game, as well as feedback of some sort. Points and levels are a common way to show progress.

- Narrative/Story/Theme: Games are also used to tell a story, and keeping a consistent theme throughout the game helps the player to be involved and immersed in the narrative.

- Flow: Players will abandon a game if they perceive it as too easy or too difficult, balance in essential when challenging the users.

- Consequences/Loss Aversion: Users need to have a level of consequences when a task was not done.

- Fixed rewards/Time dependent rewards: Rewarding milestones can motivate the player to keep advancing in the game. As for the time dependent rewards, they are events that are only available for a set period of time, making the players log into the game to obtain it.

2.4.4 Game Design Elements to Appeal Free Spirits

The following are game design elements that can be added to an application if the target is to increase adherence in Free Spirit players. This is based on the work by Marczewski [92] and Tondello et al. [49].

- Exploration: Exploratory tasks are important for Free Spirits. Creating a virtual world that allows the player to move and explore, also giving them something to find.
- Non-linear Gameplay: For this type of player, choices must be allowed in the narrative or path of the game.
- Easter Eggs: This element can be part of the exploration tasks, Free Spirits enjoy a surprise reward for looking around the virtual world and go outside of the predefined path of the game.
- Unlockable/Rare Content: Offering content that can be unlocked by completing certain tasks adds to the feeling of self-expression and value. This can also be linked to the Easter Eggs and Exploration tasks.
- Creativity Tools: For Free Spirits, being able to express themselves is very important, so allowing the ability to create their own content in any aspect of the game is key to this type of gamer.
- Customisation: This is linked to the Creativity tools, allowing the player to customise their experience and decide how they want to be seen in the game.

From the game design elements that were just listed, it can be seen that creativity and choice are essential to provide an engaging experience to Free Spirits.

2.4.5 Game Design Elements to Appeal Philanthropists

In the same line of thought as with the previous game design elements, there are certain ones that would appeal more to the Philanthropist gamer type according to Marczewski [92] and Tondello et al. [49].

- Collection and Trading: Philanthropists love collecting things in a game, and the ability to trade their collectibles with others helps build relationships and feelings of purpose, to which this type of gamer is drawn.

- Administrative roles: Philanthropists want to help others, so by adding administrative tasks, a care-taking role is offered to this type of player.

- Gifting: Being able to gift and share objects also falls into the philanthropists need to help and build purpose in the game. If there is potential for reciprocity, this gamer type can be more motivated to share.

- Knowledge Sharing: Because this type of gamer likes to help people, adding a way to answer questions and teach other players will give them purpose.

Looking into the elements that appeal to Philanthropists, it is noticeable that there is also a social component to it. By wanting to help others and building relationships with purpose, it adds another layer for the game to work. However, unlike the Socialisers, who need other players to collaborate or compete, Philanthropists can fulfill these needs and be engaged with characters of the game, such as NPCs (Non-Playable Characters) that can provide quests as the form of asking for help.

2.5 Cosy Gaming

Cosy gaming is a category of games that looks to evoke feelings of safety (low risk, no danger), abundance (basic needs are met), and softness (low stress environment visually) [24, 93, 94, 95]. In general, the goal is not about keeping a character alive, but rather to fulfill higher order needs, to self-reflect and connect with the activity at hand. Many of these games are more about self-expression and creativity, the enjoyment of doing simple tasks to create a relaxing environment for the user.

Perfect examples of cosy games are the widely known and commercially available Animal Crossing [96] and Stardew Valley [97]. Both are farm simulation games where the player builds up their new residence by doing daily tasks. In VR, the game

"Garden of the Sea" [98] also presents similar characteristics, but the interaction is more immersive, as it is the nature of VR.

In all these examples, although there are daily tasks to complete, there is no urgency to do so, and if the player does not do the task, there are no consequences beyond not collecting something that particular day.

Some could argue that cosy games are casual games, but these two genres have some differences. Cosy games focus exclusively on creating positive feelings through simple game mechanics and soothing topics. Casual games are thought to also use simple game mechanics, but not necessarily follow a story line or continue for a longer period of time, neither do they evoke a relaxing environment. These games focus on quick and easy play, in which the user can access quickly, play for a couple of minutes and leave it again. They are considered more of a way to pass the time during periods of the day when there is not much else to do (e.g. commuting, on a break, waiting room, etc) [99, 100]. Figure 2.6 shows the main characteristics of casual and cozy games to highlight their differences based on the current definitions found in the literature of these genres of games. Even though there is no official definition of cosy gaming yet, there is a trend in game development in more low-stakes games where the player can make progress without having to compete or fight for it. The nature of cosy games fulfill the game elements that appeal to Free Spirits, offering a virtual world to explore (Exploration game element) with the possibility of choosing your own path (Nonlinear gameplay). Also, it is possible to express and improve yourself through the game (Customisation and creativity tools). Lastly, given that players explore the space that is given, cosy games also add the discovery of new content that is connected to the narrative of the game (Unlockable Content and Easter Eggs).

Cosy games reward consistency rather than long hours of play, so users gain more by playing for a short time everyday. Given that there are no levels and it is an open-ended dynamic (no end to the game), players can connect with their daily activities, make progress in their own environment and accomplish long-term goals

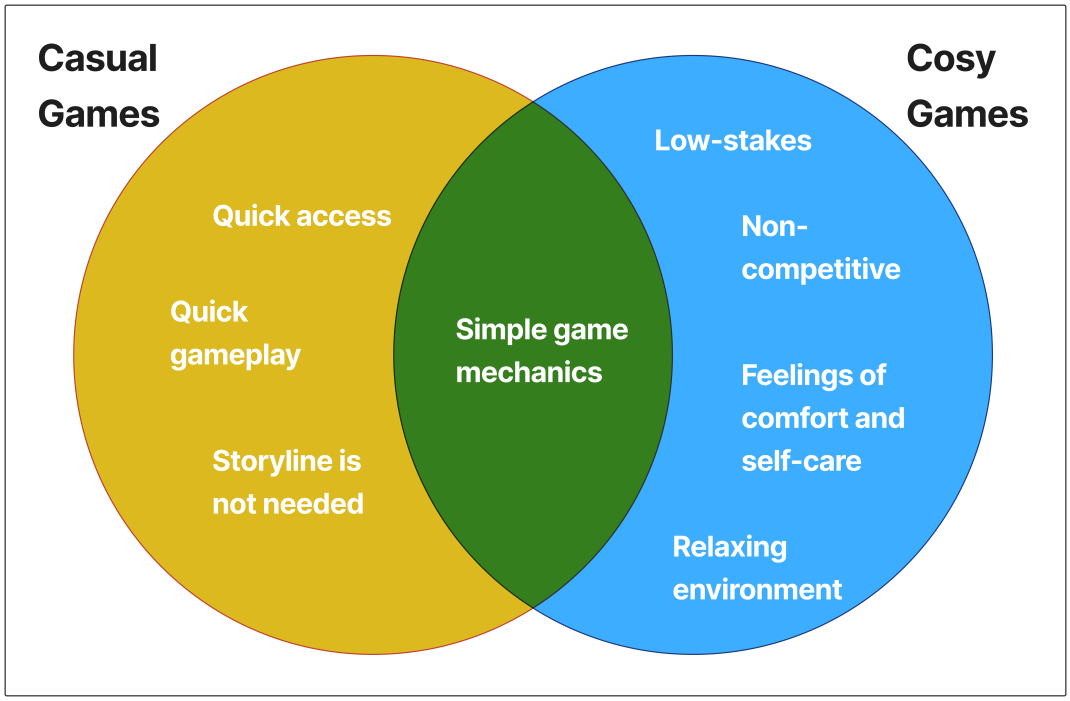


Figure 2.6: Characteristics of Casual Games and Cosy Games [99, 93].

inside the game. This means that cosy games create routines and provide a sense of familiarity. Psychologically, cosy games provide a safe space for players that are in high stress situations, a virtual world where they can forget about their current problems and they are allowed to relax and self-reflect [101].

Patients with different injuries and pathologies that have to go through painful processes and rehabilitation are already in a high-stress situation, feeling that recovery is too far away from them to reach. Gamification by adding cosy game features has the potential to improve the rehabilitation process. Little research has been done in this regard. The work of Vieira et. al. [102] gets close to this topic by determining that custom-made mini-games seem to be more effective in rehabilitation patients with neurological pathologies. Their work makes use of mini-games to provide simple tasks that are easy to understand and tailored to a specific condition. In this paper, they reported improvements in movement speed, upper-limb function, dexterity, gait, and balance. It is worth noting that this study did not specify any characteristic as cosy, and highlights the custom-made factor as the most important

one to design rehabilitation games. Another study taking an approach of mini-games was presented by Chan et al. The work presents an AR demo of a card game specifically designed for children that need voice therapy [103]. This paper identifies that cosy gaming characteristics would help patients undergoing voice therapy, given that anxiety and stress could be causing tension in their vocal tract. The game is inspired by Pokemon, creating creatures that evolve upon progress on the exercises. The authors designed physical cards of the creatures previously mentioned and other tools to perform the exercises. The AR part of the application was made mainly to appeal to the children with an animated version of the creature they see in the physical cards, but the approach could still be done without the use of AR.

The previously mentioned studies show the advantages of designing customised games for rehabilitation therapies in patients with neurological pathologies and children. In the latest work mentioned, cosy game characteristics were fundamental for the success of therapy in children. As per our current knowledge, there has been no exploration of these game elements in sport-injury rehabilitation, nor has there been the use of VR combined with cosy gaming for a home rehabilitation environment.

2.6 Immersive Technologies

Extended Reality (XR) is a term that contains a multitude of technologies depending on their level of immersion and interaction. These technologies include more familiar concepts such as Virtual Reality (VR) and Augmented Reality (AR). But also include the still discussed Mixed Reality (MR), and the less known Augmented Virtuality (AV) [104]:

- Virtual Reality (VR): The user is completely immersed in a virtual environment created from scratch. There is no overlap between the virtual and real world.
- Augmented Reality (AR): Digital elements are added on top of the real world to provide more features or information.

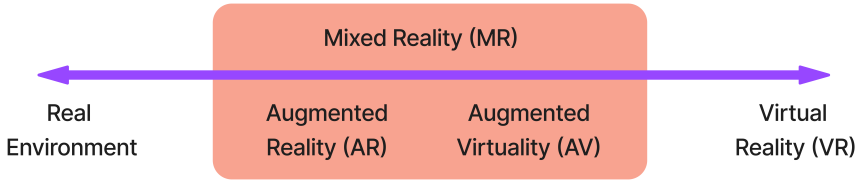


Figure 2.7: Virtuality Continuum. Adapted from Milgram and Kishino [106].

- Augmented Virtuality (AV): Real-world elements are added on top of the virtual world in order to increase realism [105].

- Mixed Reality (MR): Combines both VR and AR. The user is able to interact with the virtual and real world.

The choice of using any of these technologies depends on the application and the kind of immersion that best suits the user. A visual representation of VR, AR, and MR is depicted in Fig. 2.7 using the Virtuality Continuum (VC). We can see a progression between the real world in which we add digital elements until it becomes a virtual environment, better known as VR. As per the well-known work by Milgram and Kishino, "Mixed Reality involves the merging of real and virtual worlds" [106]. Using this definition, MR can be classified as anything that is not completely real world, but also not completely digital (VR).

2.6.1 Virtual Reality

At the far-right side of the Virtuality Continuum we find Virtual Reality, totally opposite to the Real Environment. Experts on this topic agree that VR requires a complete immersive experience, where no elements of the real world are present, and the users find themselves in a completely different (virtual) place [107].

These are the key concepts that allow us to identify this type of reality:

- Autonomy/Agency: The sense of autonomy by the user is an important characteristic of VR, in which the user can choose their own perspective on the scene, as well as how and where to navigate in the scene. This also includes

the ability to interact with objects found in that scene [21]. A sense of agency requires the user to have "global motor control, including the subjective experience of action, control, intention, motor selection and the conscious experience of will" [108]. This means that for agency to be present, the consequences of the user's actions must match the predicted consequences of actions made in the real world. For example, when a user pushes an object in the virtual world, the object must move accordingly, as if the user is pushing an object in the real world.

- Immersion: This term can has several different definitions, but in the context of virtual environments, various authors seem to agree that immersion is a feeling of being surrounded by a multisensory representation of virtual worlds that is delivered through displays and sounds [109]. Slater [110] states that immersion is "what the technology delivers from an objective point of view", telling us that the more a system matches our sensory modalities (tracking, sound direction, interaction), the more immersive the virtual world is, causing us to feel 'Present'.

- Presence: This term refers to the sensation or feeling of being in a place; meaning that all the sensory systems (perceptual, vestibular, proprioceptive, autonomic nervous systems) activate in a way that tells the brain that a person is in an specific place, meaning that Presence is a consequence of Immersion [110].

  In summary, presence is composed by two illusions in the VR world, Place illusion and Plausability illusion, which answer the questions of "Am I there?" and "Is this happening?" respectively [111].

- Embodiment and avatars: The sense of embodiment could be simply explained by how a user experiences the world inside a body interacting with the environment [108]. In other terms, it should answer the question: "Is this my body?". In Virtual Reality, avatars should give the user that sense of belonging to a

virtual body, helping to the concept of presence defined before. Kilteni et al. [108] says that for a sense of embodiment to exist, three subcomponents are needed: sense of self-location, sense of agency, and sense of body ownership.

- Proprioception: The sensation of body position and movement is proprioception, and is often not a conscious perception [112]. For example, if a person is sitting down, they are able to tell in which position their feet are without having to look at them. The same happens when people walk, a person is not constantly looking at their feet to know where they are landing with each step. In current Virtual Reality systems, the lower part of the body is not tracked, but for a lot of applications this tracking is not needed because of this sense of proprioception.

- Motion sickness: This is a common side effect when using Virtual Reality systems, caused by a mismatch of sensory information. Humans have three senses that help them to perceive their own orientation and motion: the vestibular, visual, and proprioceptive senses [113, 114]. In a virtual environment, motion sickness can arise when one "sees" movement in the display, but the vestibular system is not "feeling" any movement. The same way people get sick on a car journey.

- Haptics: Haptic technologies are developed to allow users to have a sense of touch inside a Virtual Reality system. These technologies, although still in a fairly early state of development, can contribute increasing the sense of agency and embodiment in the virtual environment [115]. Current widely-used haptic feedback includes vibration of the controllers included with commercially available headsets like the Meta Quest, HTC Vive, and PlayStationVR.

Given that the concept of Virtual Reality has been identified from other types of reality within the virtuality continuum, the next section defines the hardware components that are currently available to accomplish immersion. In the first instance, a way to display the virtual environment is needed. Currently, there are two options:

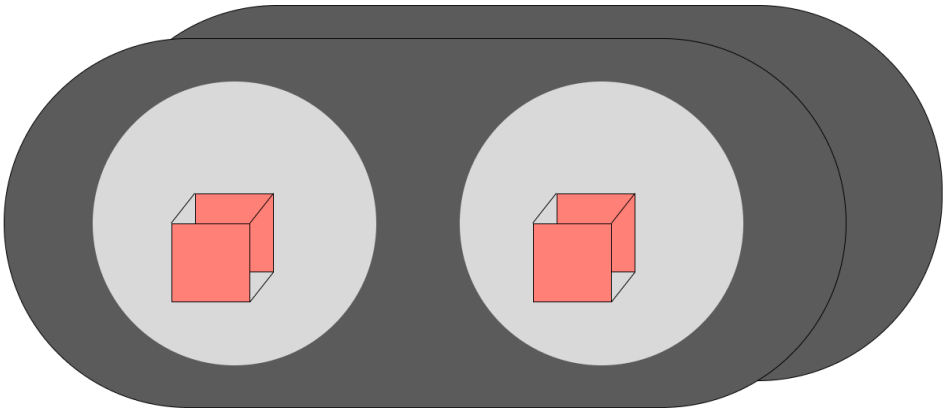


Figure 2.8: Stereoscopic view in a HMD.

- Head-Mounted Display (HMD): Today, this is the most commonly used display, with a range of commercial headsets available. The HMD may consist of a helmet or glasses that contain two screens, one for each eye. These two screens work as a stereoscopic view, imitating the way we see the world through our own eyes. Even though our eyes are looking at the same thing, the images are slightly shifted from each separate eye. This is what allows us to have perception of depth and a sense of space [20, 116]. In the same way, each screen on the HMD is slightly shifted from each other as seen in Figure 2.8.

- Room-sized Display (CAVE): This may also be referred to as "Stationary" VR, given that the user is not wearing any hardware as in the case of HMDs. This type of display consists of a stationary room in which the virtual world is projected on the walls using projectors, as seen in Figure 2.9 [116].

Once the virtual world is displayed, it is necessary to know where the user is positioned within the VR environment. When looking into hardware, consideration must be given to the type of tracking that is needed. The following are tracking options available for HMDs:

- Outside-in: Systems using this type of tracking need external sensors or base

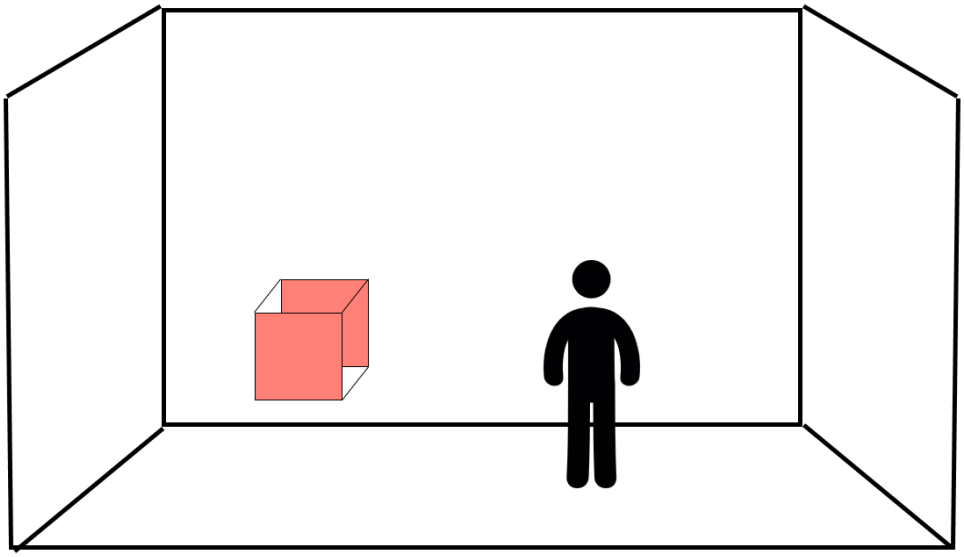


Figure 2.9: Room-sized display

stations to track the position and orientation of the headset and its controllers.

- Inside-out: Uses cameras and sensors located in the headset tracking the environment and able to track the position and orientation, as well as where the controllers are.

Figure 2.10 shows the difference between these two tracking systems.

2.7 Human Interaction in XR

2.7.1 Virtual Reality Interactions

When designing VR applications, the goal is to make the user feel present in the virtual world, which is why it is important to know how the user can interact or manipulate the virtual world. For this, the actions made by the user have to match what is happening in the virtual world, if not, this presence illusion is lost, and hence the experience may not be effective. Some of the most common interactions used in VR applications include the following:

- Selection (or pointing): This type of interaction is normally used to activate

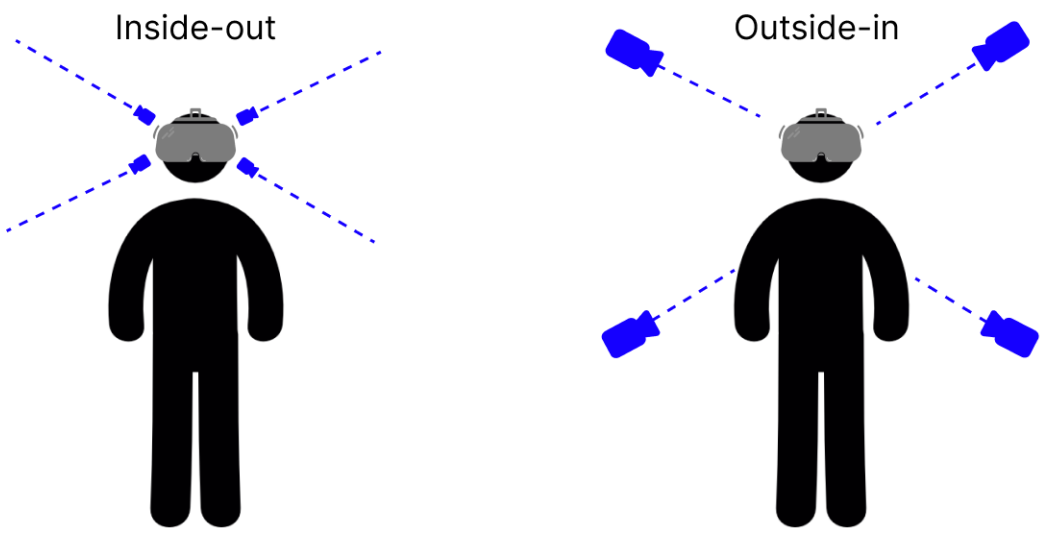


Figure 2.10: Left side: Inside-out system, where the sensors are built into the VR headset. Right side: Outside-in system, where the sensors are fixed to the environment.

virtual objects. The user can use the controllers as a hand proxy, or use hand tracking, provided that the headset has that technology available. This emulates "Virtual hands" to select objects in the virtual space.

Another method for selection is where the user can select far-away objects by casting a ray from the controllers.

- Manipulation (or grasping): As the name states, this interaction is used to manipulate, grasp, or change objects in the virtual space. The user can hover (focus an object when in range), drag (move and rotate objects), and resize (scale an object while grabbing it).

- Navigation (or travel): A very important interaction in virtual worlds is the ability to navigate through the virtual space. The user has limited space to move in their real-world environment, so it is unfeasible for them to cover large distances walking around in the virtual environment. Instead, there is an option of "teleportation", in which the controller is used to activate a travel function, point to the desired destination, and move there, as seen in Figure 2.11. Other applications use the controller to move the avatar around the

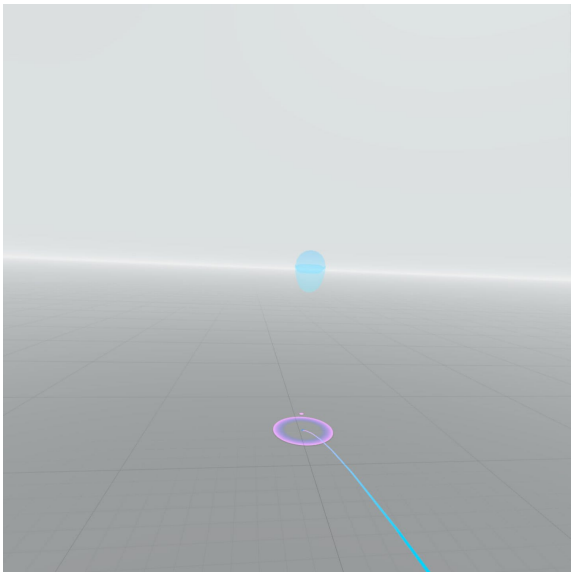


Figure 2.11: Teleportation in Virtual reality. Image captured on ShapesXR for Meta Quest by the author.

virtual environment in the same way as in 2D screen videogames. However, this is not widely used given that it is more likely to produce motion sickness in the user. Finally, for headsets that have the technology available, a user can use gaze-based navigation. In this case, eye tracking and head direction are used to determine the desired destination.

- Menus: Although real-life interactions are being emulated, menus are still needed to travel or customize the experience. Options available include fixed menus (anchored in a specific part of the virtual world), following menus (a menu that is kept in the user's view), and attached menus (attached in the user's head or hand).

2.8 Applications

Extended reality (XR) has the capabilities to offer new ways of interaction for many tasks, opening possibilities into the gamification in a number of applications (e.g. healthcare, education, skills training, etc). A potential application that could benefit greatly from XR is physical rehabilitation, which is necessary for the recovery of movement after an injury. Currently, this gets low adherence rates from the patients.

2.8.1 Physical Rehabilitation

Previous works related to the use of VR in physical rehabilitation focus on patients that have suffered a stroke or other neurological injury. Some studies focus on regaining motor control using VR and conclude that VR has the potential to improve motor skills, balance, and pain level in patients with pathologies and conditions such as stroke [117, 118], brain damage [119], spinal cord injury [120], Parkinson's disease [121, 122]. Although these studies have shown that there is improvement in regard to the patient's physical state, there are still questions as to how effective long term use would be, whether patients would keep using it without supervision, and which type of virtual experience would suit each condition to give better results.

In the case of rehabilitation of knee injuries, some studies have focused on the perceptual impairments after a lower extremity ligament injury, e.g. using VR to do balance training, or by providing a scenario where the patients move away from conscious motor control [123, 124]. In addition, VR combined with wearables are being used to identify the injury risk of athletes, or evaluate whether an athlete is ready to go back to sports, but not as a way to support regaining their range of motion as part of their HEP after the injury [125, 126].

The work of Chen et. al. [127], describes the psychological benefits of Virtual Reality during rehabilitation therapy on patients with spinal cord injuries. This study showed that a VR system can ease patients' tension and induce calm during the therapy.

In terms of technology used to include lower limb motion in the VR environment, some studies have included RGB-D camera-based motion capture systems [128, 129], infrared complementary metal-oxide semiconductor (CMOS) image sensors along with depth sensors [130], and Microsoft Kinect [131, 132, 133, 134]. The use of Inertial Measurement Unit (IMU) sensors has also been used to track lower limbs using gamification in a rehabilitation setting [135, 136]. However, these studies have used the IMUs to track and display lower limb movements on a phone or tablet, but not within an immersive environment. This identifies an opportunity to explore the

effectiveness when using virtual reality.

The previously mentioned works focus on different parts of the rehabilitation process, such as the correct performance of tasks, evaluation of sport readiness, and injury risk prevention. As yet, there is no study focusing on how to improve patients' adherence in an unsupervised environment in order to comply with their rehabilitation programme. Furthermore, previous studies using VR technology need external cameras and equipment in order to track lower limb movements. This makes the home rehabilitation setting more complicated to set up for the user. This project aims to determine gamification elements that could improve motivation of patients following a HEP in a VR environment.

2.9 Summary

Designing a home rehabilitation system requires careful consideration of the technology that is applicable and suitable for the target users and environment. This chapter starts by discussing the main stakeholders of the project and research related to rehabilitation for amateur athletes. Then, a review of gamification within the rehabilitation domain is documented, including references to the HEXAD UserGamer Types framework which helps to determine the types of games that people are drawn to. This leads to the concept of the cosy genre of games, which appeals to certain types of users that align with motivational needs in rehabilitation care. Finally, a description of current immersive technologies that are available nowadays is depicted, how people interact with these new "realities" and their potential uses in the field of rehabilitation.

A number of immersive technologies were reviewed for this application, in which fully immersive VR has shown to have psychological benefits in patients and also offer the advantage of portability, increasing the chances of using this application at home unsupervised. Studies have shown that gamification is useful to increase motivation and adherence in otherwise repetitive tasks such as rehabilitation. However, no previous work has been done specifically for users identified as Free Spirits.

Given that Free Spirit gamers are one of the most common gamer types [49], and their characteristics and game elements are consistent with cozy games, this research will focus on creating a gamified rehabilitation application for Free Spirits.

The combination of cosy gaming and Virtual Reality have the potential to help overcome these barriers. The gaming elements that a cosy game dynamic offers can help patients with their fears and feelings of isolation by providing a low-stress environment where they can also feel safe while playing. Virtual Reality on the other hand, provides portability, so the patients don't have to travel to another location. Also, immersion and digital guidance in the virtual environment are useful when managing expectations and show the exercises they need to perform.

This review highlights the current gaps and opportunities in this field and identifies the relevant stakeholders in this work, which form the main research questions of this thesis. The research questions are established in Chapter 1. RQ1 is addressed in Chapter 3, RQ2 and RQ3 are addressed in Chapters 4 and 5. In the next chapter, the design and development of the application is described.

Chapter 3

Design and Development

3.1 Design

The previous chapter defined the target users and identified their pain points (Section 2.3.2 and 2.3.1. These factors were then used to inform the design of the first prototype application. In order to do this, a series of gamified scenarios were created to guide and motivate the user through specific exercises they need to perform for rehabilitation. The gamified scenarios and the application as a whole intend to increase rehabilitation adherence through gamification, rather than assessing and evaluating whether the exercise has been performed in the correct form. This chapter outlines the design and development of the *CozyACL* application.

3.2 Gamification Elements

Previous rehabilitation applications focus on collecting points and getting rewards to get to the next level, as discussed in Section 2.4). Those game elements have proven to be effective across a range of conditions and injuries that need physical therapy. Normally, these applications appeal to Achievers and Players, as seen in Section 2.4.2. The purpose of *Cosy ACL* is to focus on reducing stress and to let the user exercise at their own pace while at the same time keeping consistent in their exercise regime.

For the design of the first iteration of *Cosy ACL*, the game elements have been designed to appeal mainly to Free Spirits. Some game elements for Players have been added as well. These game elements include:

- Exploration tasks: The user will be able to explore the virtual environment.
- Non-linear gameplay: The game doesn't use levels as a means to track progression.
- Unlockable content: The user can unlock more content from the environment as they keep playing.
- Virtual Economy: Gameplay requires collecting some sort of currency in order to unlock content.

3.3 Narrative of the Game

Cosy ACL is about the journey of healing and overcoming adversity in your own terms. In this game, you find yourself in a deserted island after the unfortunate shipwreck of a ferry you were taking to get to a cutting edge rehabilitation centre.

In order to make this island your new home, you must build your surroundings, and this task often requires a lot of physical work. It is especially difficult for you after your ACL surgery!

Fortunately, you figure out that picking up materials with specific movements not only makes the task easier, but it also serves as part of your recovery!

3.4 Game Mechanics

In *Cosy ACL*, the player is in a virtual environment that is presented as a deserted island. The player can move and explore freely around the space. In this space, there are points where materials or resources can be collected by the player. The resources available are: Wood, Stone, Sand, and Brick.

In order for the player to collect a material, they need to perform a certain number of sets of an exercise. At the end of the set, the material gets added to the player's inventory to use later.

In other zones of the island, there are objects that can be built by the player if they have enough resources.

The virtual environment counts with three main points of interest:

- Resources locations: Resources or materials to be collected will be spread out around the island for the player to find. There is no specific order to find these. This addresses the need for exploratory tasks and non-linear gameplay.

- Exercise mini-games: These are the locations where the exercises are performed by the player. When the player locates a resource, they will need to enter into a mini game in order to collect it. When players accept to enter into the mini-game, they get teleported to another zone where they can execute their repetitions.

- House: The goal of collecting resources is for the player to be able to get enough of these materials to be able to "build" or "purchase" elements for their new home in the island (Virtual economy and unlockable content).

To avoid over-exercising, the collection of resources can only be done once a day. Once the needed repetitions are done and the user collected the resources of the day, it is not possible to play the mini-games until the next day. This way, if the user wants to progress "faster", they need to log into the game everyday so they don't miss the collection of resources.

3.5 Storyboards and Wireframes for Mini-games

Storyboards are a common way to convey ideas before turning into the development phase of a product. Essentially, a storyboard is a narrative of the application, made

with a sequence of images in order to show a more complete story about how people will interact [137, 138].

Storyboarding in VR applications can be more complicated than a 2D application, given the nature of VR, we need to take into account all the surroundings and interactions that occur in a 3D space. When there are complex mechanics of interaction involved, it can be difficult to show ideas. Currently, design teams sketch on a 360° storyboarding template, but this limits the changes that can be made when reviewing that storyboard. Others prefer to use role-playing to express the ideas for the application, but this could also be difficult if there is not enough people to do it this way [139].

Wireframes on the other hand, are basic schematics used to visualize the User Interface (UI) of a digital product. For VR applications, menus are still needed to interact with the application, and we will discuss the design of these menus in terms of what is shown to the users and how it is being shown [140].

In this step, the storyboards and wireframes can be evaluated and allow for corrections before going to the next design phase: Prototyping.

The following subsections discuss the creation of storyboards for each exercise that was selected in collaboration with a physiotherapist: Forward lunges, Lateral lunges, squats, and heel raises. For the creation of the storyboard, the software called "Storyboarder" [141] is used, which is normally used for cinematography storyboarding, but the software has a "shot-generator" feature to allow for a 3D scene, where characters and 3D models can be added. Two other exercises, single-leg deceleration drill, and lateral shuffle, were considered for inclusion in this first iteration of *Cosy ACL*, but after careful consideration it was decided to not include them, as discussed below.

3.5.1 Single-leg Deceleration Drill

Most of the time, ACL injuries occur due to non-contact movements, this includes deceleration and landing tasks. Training for these tasks can help prevent an injury

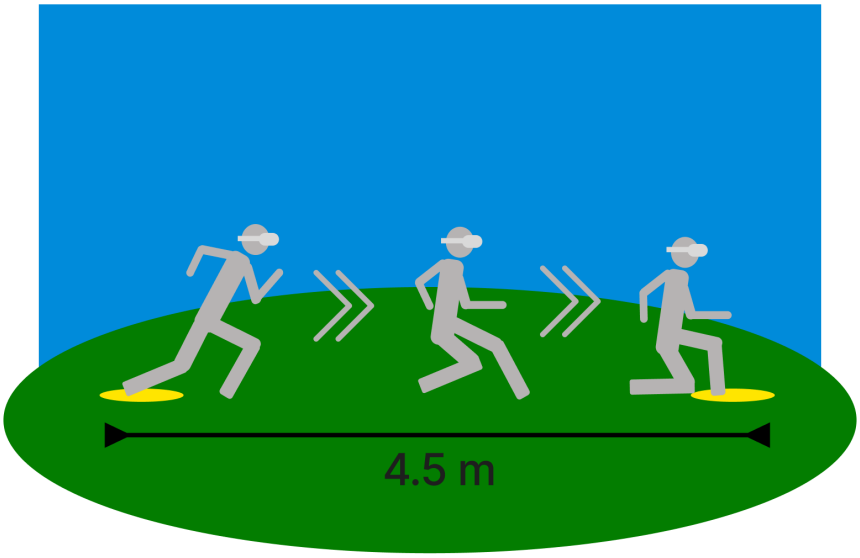


Figure 3.1: Illustration of deceleration drill.

[142], but once you recover from an ACL, it can be a very challenging exercise to perform, causing fear to the patient (Kinesiophobia). The exercise consists of sprinting from one marked point to the next, decelerating on time and landing on one leg on the final mark. Although it is an important exercise to recover this ability, it is also necessary that the physiotherapist closely follows the progression before the patient is able to perform this exercise [143]. This is why it was decided to not include this exercise in the first iteration of the game, given that participants may not feel confident to do this exercise and there would be no clinical supervision during the task. Also, one of the limitations of the use of VR at home is the lack of available space. For this exercise, at least 4.5 meters of walking space is needed (See Figure 3.1), and even though we can provide this space in a laboratory setting, it is not feasible for home use.

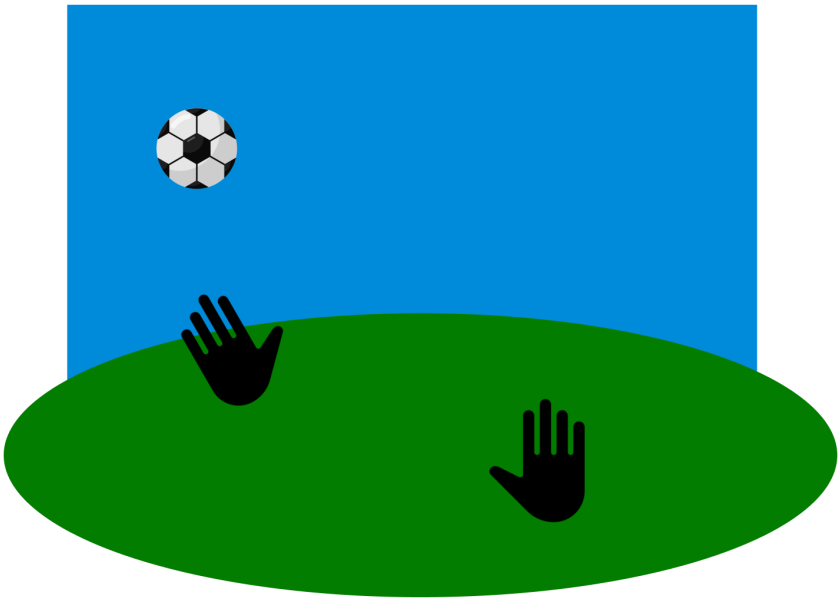


Figure 3.2: Illustration of lateral shuffle game

3.5.2 Lateral Shuffle

Following the same line as with the deceleration, a lot of the ACL injuries occur in sudden changes in direction from the player. Lateral shuffles require the person to run side-to-side. while not allowing the legs to cross in the middle [144, 145]. This is also a good exercise to evaluate injury risk, but given the speed needed to do the movement, it was also decided not to include this exercise in the first iteration of the game. Figure 3.2 shows an illustration of the idea for this exercise, emulating a goalkeeper who needs to catch a soccer ball. The same issue with space arises with this exercise, making it not feasible for home use if the appropriate amount of space is not available.

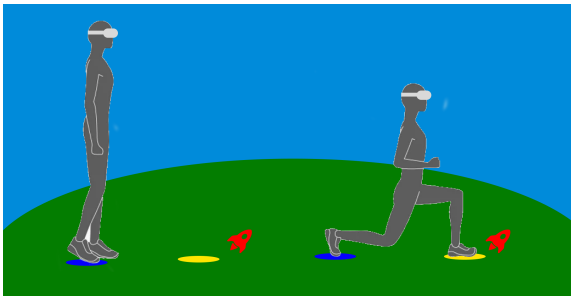


Figure 3.3: First drawing to illustrate the game dynamic for the forward lunges exercise.

3.5.3 Forward Lunges

Lunges are a type of exercise that helps the patient to strengthen their knees. For the forward lunges exercise, the user has to step forward, then lower their hips until both knees are bent approximately 90° as shown in Figure 3.4. After that, the user pushes off their front heel in order to return to the starting position. This exercise is normally appropriate for any stage of ACL rehabilitation [146]. The main idea of the game is that the user has to place their left and right feet in the right colors, making them do the lunge position, in order to complete the repetition.

The storyboard with the narrative of the interaction can be seen in Figure 3.4.

3.5.4 Lateral Lunges

Lateral lunges, although similar in name to forward lunges, this exercise strengthens not only the lower body, but also provides some balance training and core work. For this exercise, the user has to take a long step to one side. Then bend the knee that took the step while the other leg remains straight (As shown in Figure 3.6). For this movement to take place, the user also has to sink the hips back to lower into the lateral lunge position. To return to the starting position, the user pushes the foot of the bent leg until it is possible to take the initial step back. This exercise is also appropriate for any stage of rehabilitation [146]. In this mini game, the player needs to perform a lateral lunge to be able to reach the object.

The storyboard with the narrative of the interaction can be seen in Figure 3.6.

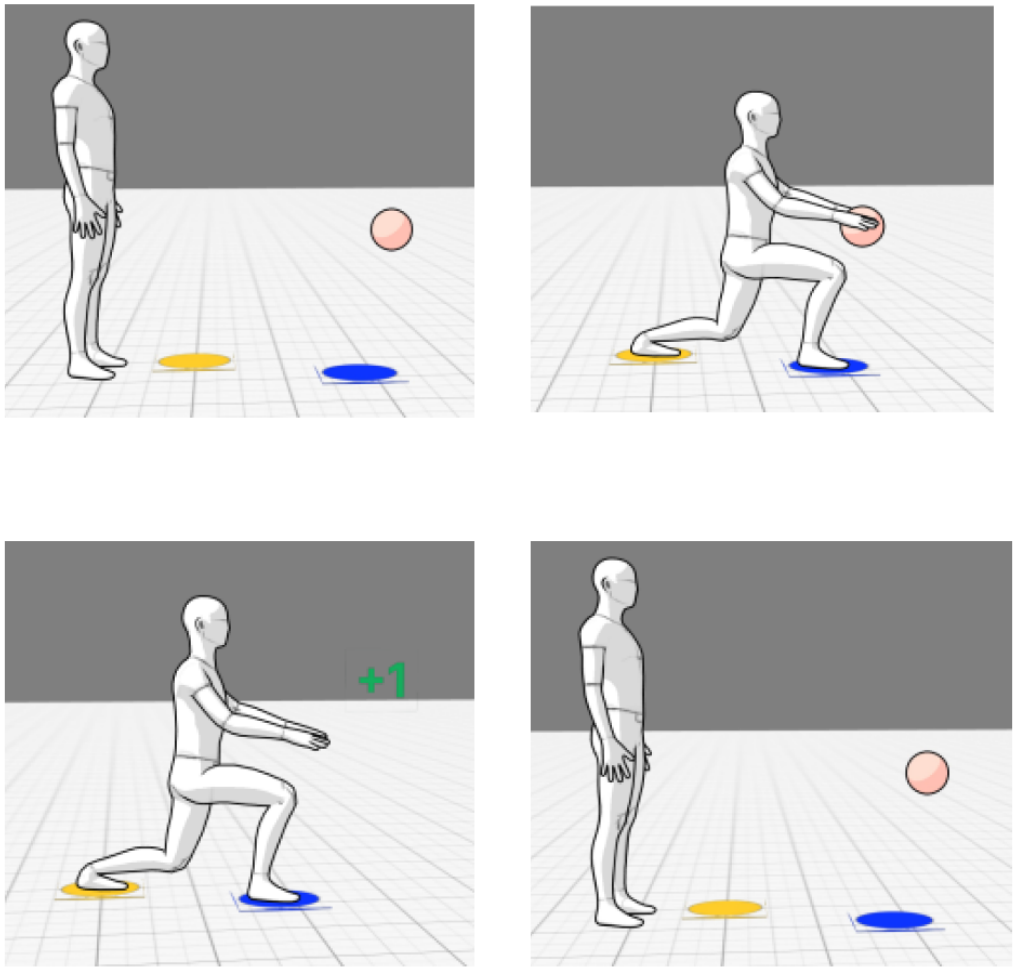


Figure 3.4: Storyboard on the game dynamics for the game of forward lunges. The user needs to reach for the objects by doing forward lunges.

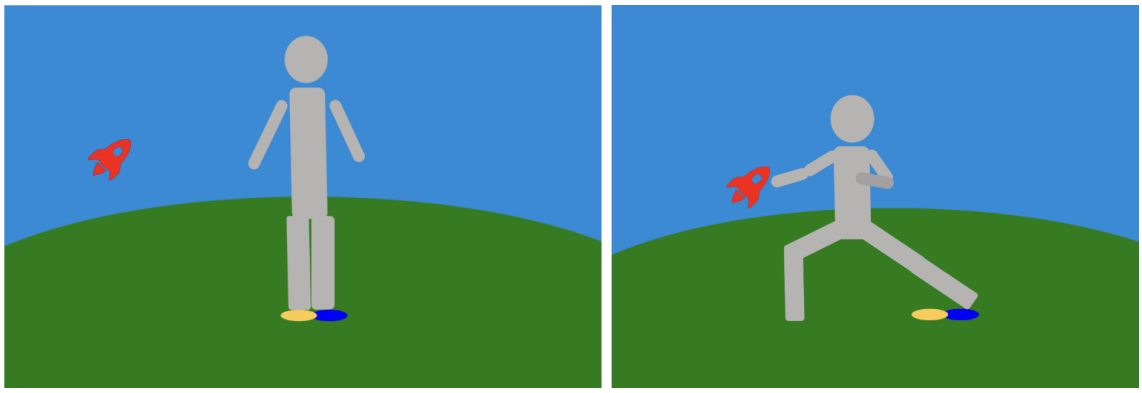


Figure 3.5: First drawing to illustrate the game dynamic for the lateral lunges exercise.

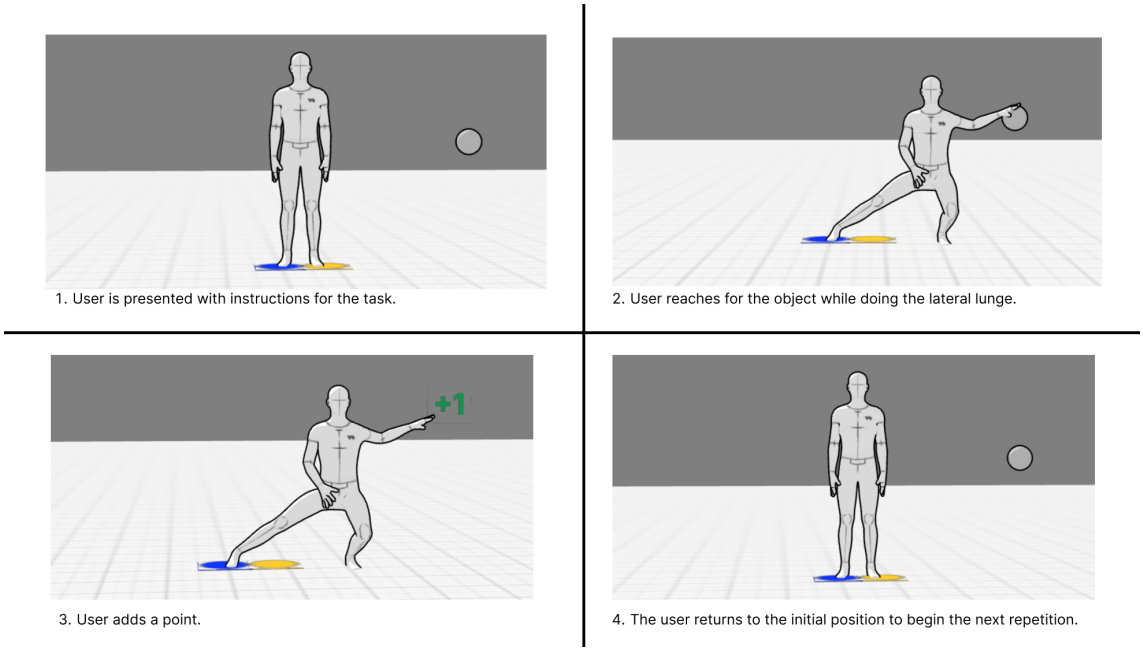


Figure 3.6: Storyboard on the game dynamics for the game of lateral lunges. The user needs to reach for the objects by doing lateral lunges.

3.5.5 Squats

Squats are a very useful exercise for ACL rehabilitation, given that many large muscles are involved by doing just one movement. In this exercise, the user starts from a standing position, then lowering the body by bending the knees and hips as if they were going to sit on a chair. Once the thighs are parallel to the ground, the user pushes back to return to the initial position. This is also an exercise that is safer to perform in any stage of the rehabilitation [147]. In this mini-game, the player has to perform a squat to pick up a sack of sand from the floor.

The storyboard with the narrative of the interaction can be seen in Figure 3.8.

3.5.6 Heel Raises

Heel raises are prescribed from phase 1 of ACL rehabilitation, this is because this exercise strengthens the calf muscles and is considered effective for strength development [148]. From a standing position, the user lifts their heels off the ground by pushing onto the balls of the feet. The user must hold the position for one or two seconds and then come back to the starting position by slowly lowering the heels to



Figure 3.7: First drawing to illustrate the game dynamic for the squats exercise.

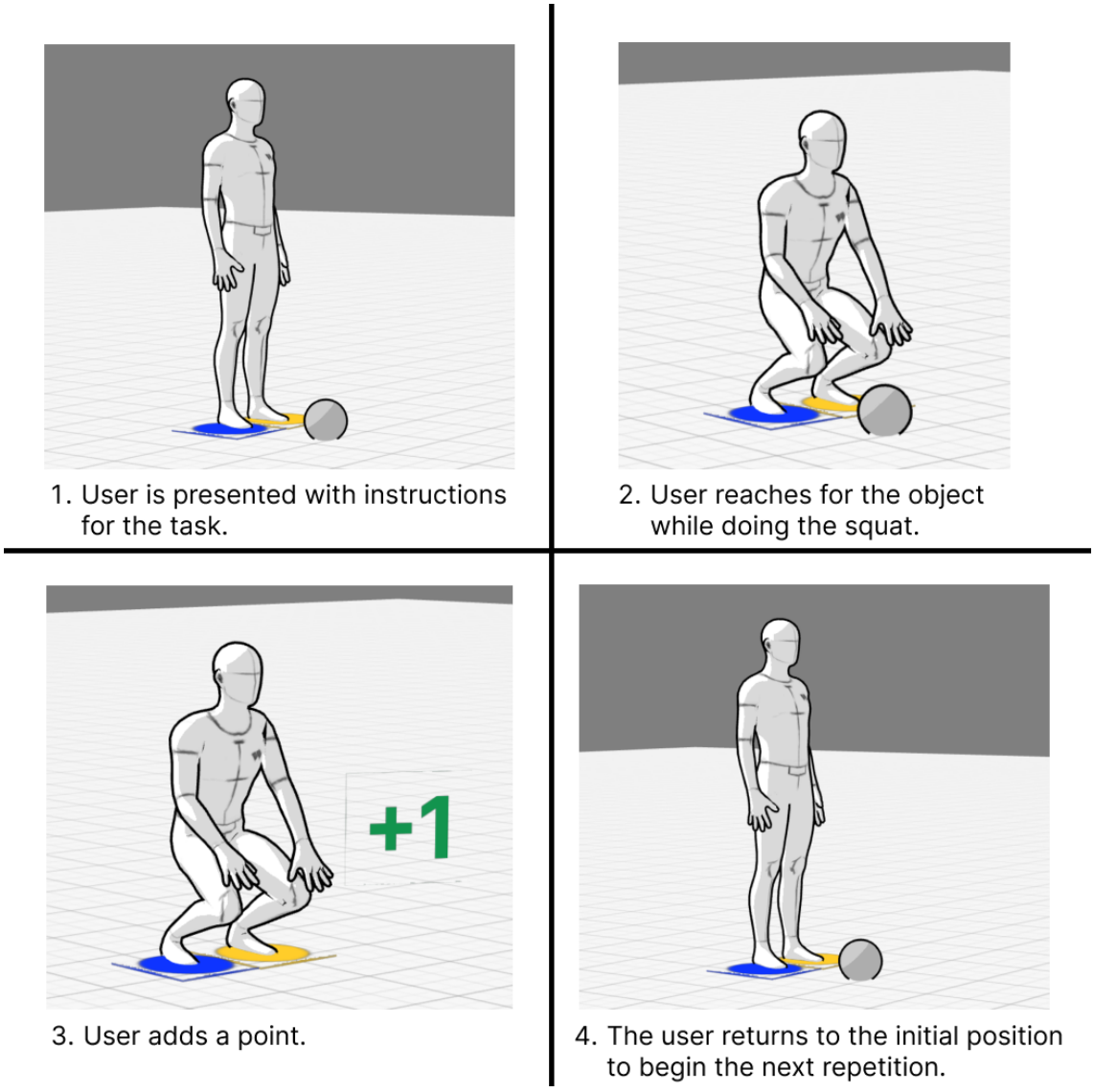


Figure 3.8: Storyboard on the game dynamics for the game of squats. The user needs to reach for the objects by doing squats.



Figure 3.9: First drawing to illustrate the game dynamic for the lunges exercise.

the ground.

The storyboard with the narrative of the interaction can be seen in Figure 3.10.

3.6 Prototype

Prototyping is a crucial step when developing these kind of applications. We need to test whether the game dynamics and the user interaction are what we are looking for before diving into a more time-consuming development. For the prototyping, mid-fidelity scenarios were prototyped using ShapesXR [149], a VR platform created for prototyping and spatial design. This application is available in the Meta Quest Store.

ShapesXR was chosen to create the mid-fidelity prototypes given the set of tools that it has available to create a 3D scene in an intuitive way. The platform is designed for the creation of interactive prototypes in Virtual Reality or Mixed Reality. Interactions that can be added include: On click, On hover enter, On hover exit, and After delay. These interactions are still very basic for the application we want to create, but they are enough to showcase the idea of the application.

For this prototype, Mixed Reality was used, adding the elements that the user has to interact with. Mixed Reality was used instead of complete immersion for this prototype to focus on the interactions of the mini-games instead of the design of the

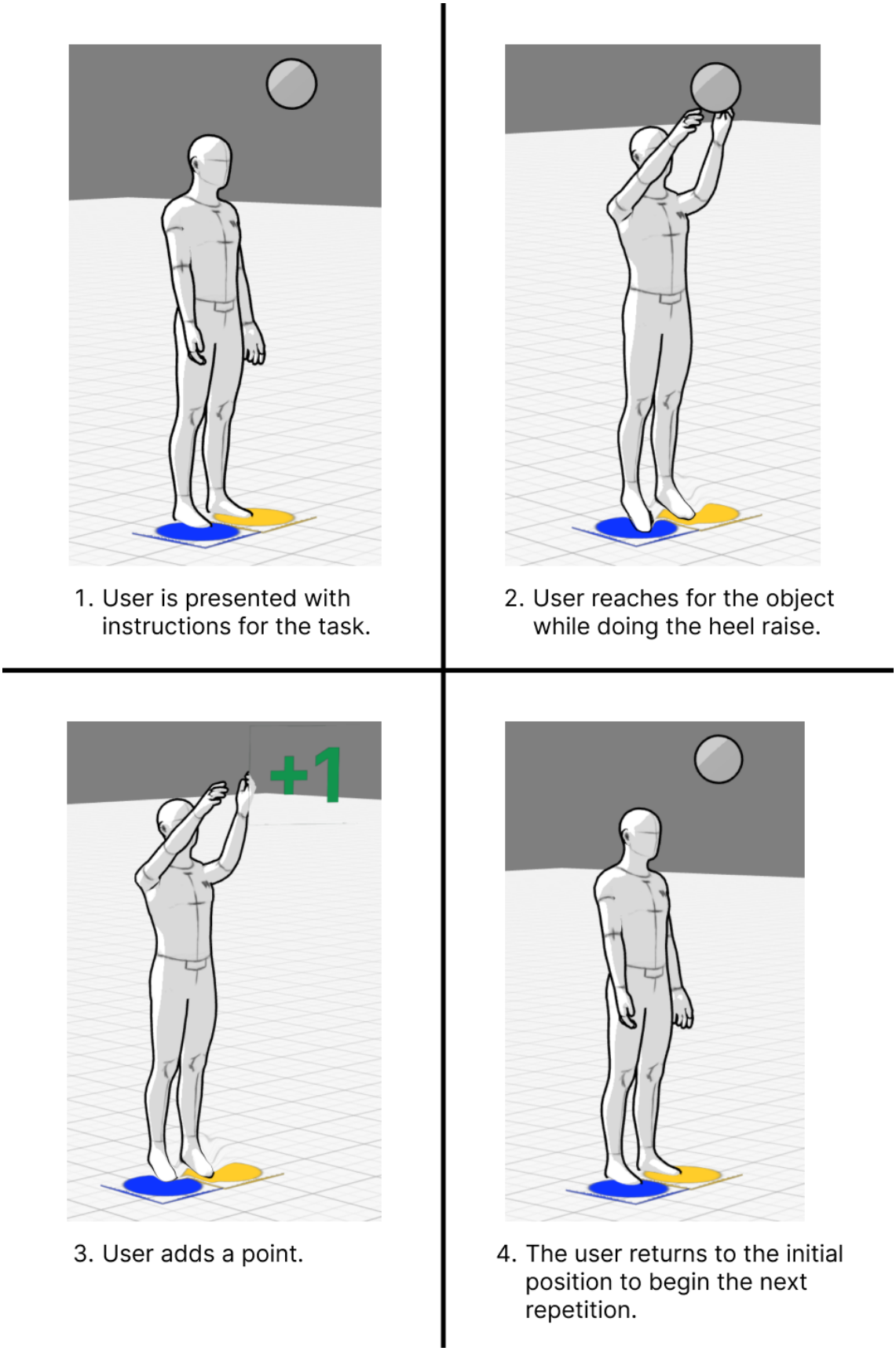


Figure 3.10: Storyboard on the game dynamics for the game of heel raises. The user needs to reach for the objects by doing heel raises.

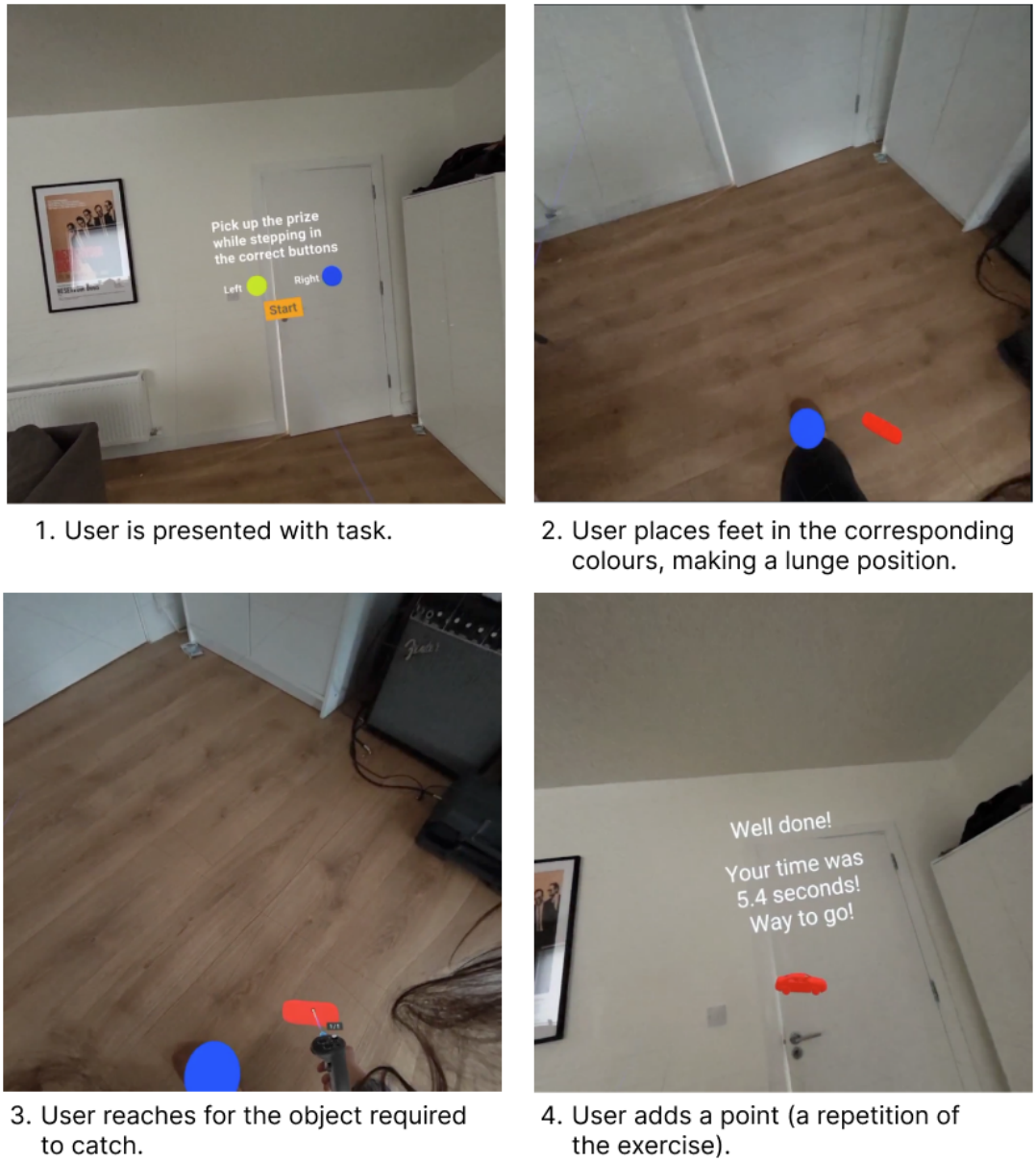
virtual environment. The interactions used in this prototype include On Click over the object that the user must grab. In this prototype the controllers use raycasting, but not grabbing as anyone would do in the real-world.

This prototype was only tested by the researcher to evaluate its feasibility in user testing. A limitation with this prototyping tool has to do with the way of presenting it to real users. This tool works by watching slides, going forward or backwards as needed. The interactions described before help to give a more natural interaction, but it is easy to make a mistake with the controllers and pass to the previous or next slide. Another limitation at the time of working in this prototype is that teleportation is not possible, so the free exploration of the virtual environment is not possible. Even though this tool had its limitations, and wasn't suitable for user testing, it was useful for creating a draft of the mini-games that we wanted to include before developing any further.

Working from the storyboard shown in Section 3.5.3, a mid-fidelity prototype was created using ShapesXR in the Meta Quest 3. In Figure 3.11, the narrative of the tasks as seen from the user's point of view in the ShapesXR app is depicted.

3.7 Summary

This section presented the narrative and game mechanics of the game, as well as the initial prototyping of the exercises to be tested. For the purposes of this project, four of the six initially proposed exercises are included in the application, but the catalog of available exercises can be expanded after the effectiveness of the game is tested. In the next section, the development of a high-fidelity prototype is shown, including the selection of hardware used, and more details of the game mechanics that include the game elements that appeal to Free Spirits.



1. User is presented with task.
2. User places feet in the corresponding colours, making a lunge position.
3. User reaches for the object required to catch.
4. User adds a point (a repetition of the exercise).

Figure 3.11: Prototype of the lunges game as seen from the user's point of view.

3.8 Hardware

The hardware needed for this project consists of a VR headset and the necessary motion sensing tools to obtain the appropriate measurements. In this section, details on how these elements were chosen are discussed.

3.8.1 VR Headset and Platform

Initially, for this part of the work, the Meta Quest 2 was chosen as the headset to be used in this application. When comparing to other brands such as the HTC Live, and SteamVR, we found that the Meta Quest 2 had some advantages over the others:

Studies suggest that the positional accuracy of the HTC Vive headset is not good enough for rehabilitation purposes, given that the headset uses a reference plane that is tilted away, affecting the measurements, the studies also show position accuracy of 1.9mm [150, 151].

Other studies that compared the Meta Quest 2 with the SteamVR tracking system, showed that the Meta Quest 2 had higher accuracy, and makes it suitable for research and industry [152, 153]. These studies show an accuracy of $\approx$ 0.5mm [154].

In addition to the characteristics of the headsets, prices were also compared, and the Meta Quest 2 was also the most affordable. Another advantage of this system is that it is standalone and not tethered to a computer, giving the person more freedom of movement while immersed in the virtual environment, given that there are no cables around. Also, by having inside-out tracking, no other equipment needs to be installed in a room. All these points determined our choice of headset.

The Meta Quest 3 launched on October 2023, with a more ergonomic design of the headset. The pass-through feature on this headset can help in creating some tasks that may require more visual feedback from the surroundings. There are no studies yet that clarify the position accuracy of this headset, but we can assume that it can be as good as the Meta Quest 2 or better, given that it is a more developed

Headset	Accuracy	Cost	Standalone/ Tethered	Type of tracking
Meta Quest 2	0.5mm	€249.99 (128GB)	Standalone	Inside-out
Meta Quest 3	No studies yet	€549.99 (512GB)	Standalone	Inside-out
HTC Vive Pro 2	1.9mm	€1399 (Full kit)	Tethered	Outside-in
Valve Index VR (SteamVR)	7mm	€1079 (Full kit)	Tethered	Outside-in

Table 3.1: Comparison of headset characteristics.

technology by the same company.

In Table 3.1, a comparison of characteristics of different commercial headsets is shown.

3.8.2 Wearable Sensors

For the selection of wearable sensors the following characteristics have been taken into account:

- Ability to stay in place
- Accuracy
- Position tracking of the legs (knee joint and ankle and hip position)
- Comfortable for the user
- Ease of use for the user

In Table 3.2, a basic comparison of three sensors that have been considered is shown. Table 3.3 shows additional characteristics fo the sensors. The Shimmer3 IMU sensors is a wearable wireless sensor with integrated 10DoF inertial sensing. Through an accelerometer, gyroscope, and magnetometer, it is able to deliver 3D orientation estimation [155]. These sensors also incorporate Bluetooth connection. For our purposes, two sensors for each leg are needed in order to obtain orientation from each sensor and calculate the angle between the two, giving us the knee angle. The main issue we have encountered when using these sensors, is that the Bluetooth

connection was found to be unreliable, even with their proprietary software, and an essential part of a home system is ease-of use and compatibility. Three different computers were trialled to connect the sensors, two of which the sensors appeared to be paired, but no real connection was done. On the third computer, the sensors paired correctly and calibration of the sensors was done. When testing the sensors, raw data was obtained, but after a few trials, the connection seemed to get lost and it was not able to connect again in order to calibrate. Also, for the Shimmer sensors, calibration is needed every time they are used, which is acceptable within a research environment, but for a person using the system at home it is very inconvenient and adds complexity to the system. Calibrating the sensors each time the patient needs to use the system would add another barrier to get their exercises done. It is likely that patients would not know how to do the calibration process on their own, and with this additional step they may choose not to use the system at all.

The other option that was considered was the MTw Awinda Motion Trackers by Movella (now Xsens), which are sensors widely used to capture human motion [156]. The main issue with these sensors is that all their software and wireless communication is proprietary, so it is not possible to get raw data from these sensors. Also, integration with Unity, although it seems very straightforward, requires a plugin that can only be acquired through a yearly subscription to their development software, which is expensive. The high cost of these sensors and software would make the system unfeasible in terms of access for patients. For this sensor system it is also necessary to obtain a set of five sensors to measure the lower body movement. In another note regarding IMU sensors, given that more than one sensor needs to be placed on the user, the set up can also get more complicated.

A third option is to use a bend sensor, in this case the Bendlabs 1-axis sensor was tested [157]. This sensor is able to give you the angle between the beginning and the end of the sensor. The sensor kit comes with a Bluetooth module and a battery. Calibration is very easy to do by placing the sensor on a flat surface to set it to 0 degrees. With only one sensor located on the knee, it is possible to get

the knee angle that we are looking for. A comparison between bend sensors and IMU sensors to measure the knee angle was carried out in the work by Gibbons et. al. [158], in which the results show better accuracy in angle measurement with the bend sensor compared to the IMU sensor. An additional advantage is that the bend sensor is easier to set up, and therefore it is likely that the users will not find it as troublesome as the process to calibrate an IMU sensor. The main issue with using this sensor is that it only provides the angle of the knee and it is not possible to measure the position of other joints (ankles, hips) that comprise the lower-body movements.

Lastly, the Sony Mocopi Sensors were considered as they are marketed to the general public to capture motion data easily [159]. These sensors offer Bluetooth communication through their own app as well as motion data and video recording. The kit consists of six 6DoF sensors (3DoF Accelerometer + 3DoF Angular rate sensor) and they are placed as shown in Figure 3.12. Each sensor weighs 8g and their dimensions are 32mm in diameter and 11.6mm in height. As with the other IMU sensors discussed, these sensors also need to be calibrated each time the user needs to capture movement. Calibration for the sensors is done through their mobile app without the need for a paid subscription. First, the sensors need to be detected and connected before being placed on the body. Then, the app prompts the user to stand straight and take one step forward after hearing a beeping sound. After the step is taken, the calibration is complete, unless the step was taken incorrectly. The main issue encountered while calibrating the sensors has to do with the initial Bluetooth connection, which would sometimes take a long time due to one or more sensors being unable to connect with no apparent reason for this error to occur. The only solution was to exit the application, start over, and expect all the sensors to connect that time. When testing with participants, this error occurred many times, extending the time of the test and most of the time, not being able to use them. In terms of data and recording, the mobile app can record the position of the sensors and provide a BVH file, which is a common format for motion capture data.

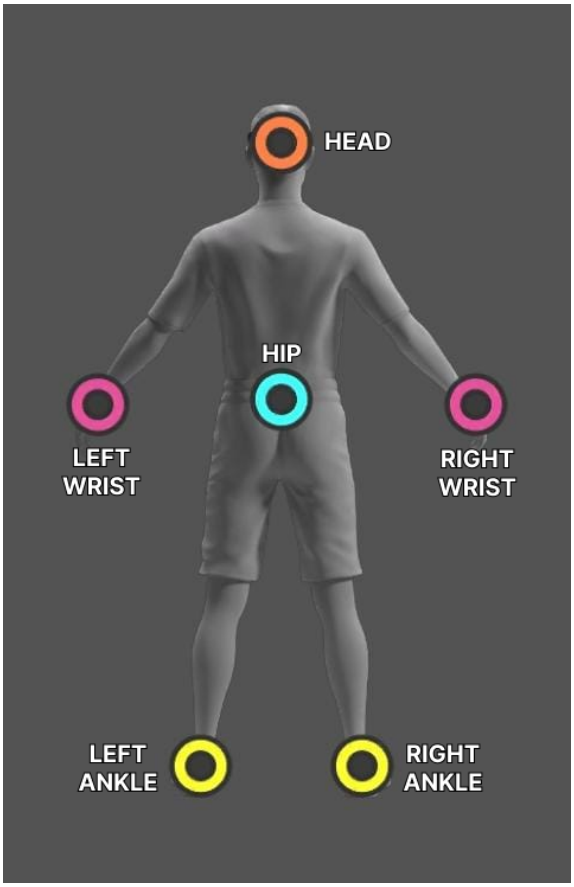


Figure 3.12: Placement of Sony Mocopi sensors [159].

The app can also record a video of the motion that is being captured, but it is not possible to record a video and capture motion data at the same time. The motion recording was done in a couple of participants, but when the data was exported, the data turned out to be corrupted, which means that the motion data was not captured correctly from the application. Also, after around 5 minutes, one or more of the sensors would lose the initial calibration and capture the wrong movements, making necessary to do a second calibration.

In Table 3.4, a comparison of the characteristics mentioned at the beginning of this section is shown.

The collection of motion data is a valuable source of information for physicians to track the progress of their patients, but commercially available solutions of wearable sensors for this purpose still need to improve in terms of ease of use. It would be feasible to use any of these solutions in a supervised environment, where these technical difficulties can be solved. The goal of this project is to provide a solution

Sensor	Dimensions (mm)	Metric measured	Notes
Shimmer3 IMU sensor	450 x 330 x 10	Acceleration, angular velocity	Bluetooth available, needs constant calibration
MTw Awinda Wireless 3DOF Motion Tracker	47 × 30 × 13 mm	Acceleration, angular velocity	Wireless communication available, needs proprietary software, no access to raw data.
Bendlabs 1-axis sensor	100 x 7.62 x 1.27	Angle	Bluetooth available, easy to use, one initial calibration is needed.
Sony Mocopi Sensors	32 x 32 x 11.6	Acceleration, angular velocity	Bluetooth available, initial calibration needed, motion data and video available

Table 3.2: Comparison of dimensions and metrics measured of sensors.

Sensor	Streaming vs on device	Local storage	Sampling rate	Battery life
Shimmer3 IMU sensor [155, 160, 161]	Streaming	8 GB microSD card	Up to 1024 Hz	≈14 hours
MTw Awinda Wireless 3DOF Motion Tracker [156, 162]	Streaming	N/A	1000 Hz	≈12 hours
Bendlabs 1-axis sensor [157]	Streaming	N/A	1-200 Hz	N/A
Sony Mocopi Sensors [159]	Streaming	N/A	Up to 60 fps	≈ 10 hours

Table 3.3: Comparison of technical characteristics of sensors.

Sensor	Ability to stay in place	Accuracy	Tracking of the leg	Comfort	Ease of use for the user
Shimmer3 IMU sensor	✓	✓	✓	✓	✗
MTw Awinda Wireless 3DOF Motion Tracker	✓	✓	✓	✓	✗
Bendlabs 1-axis sensor	✓	✓	Only knee joint	✓	✓
Sony Mocopi Sensors	✓	✓	✓	✓	✗

Table 3.4: Sensor comparison against the characteristics needed for the application.

that would eliminate the barriers described in Section **??**. The current state of wearable sensors for motion capture does not allow players to use them reliably in an unsupervised setting.

3.9 First Iteration of Game

The first iteration of the game was developed using Meta Horizon Worlds [163], included in Meta Quest 3. This software allows you to create a virtual environment and easily place 3D assets. Another feature of this software is that interactions can be made using scripting.

As explained in Section 3.4, the user will be able to freely explore the space, which in this case is a deserted island. In Figure 3.13, a map of the virtual environment that was developed is shown. In this map, the locations of interest as described in Section 3.4 are also depicted.

3.9.1 Resource Locations

Spread throughout the island, the player will be able to locate and collect four different materials:

- Wood: In order to collect Wood, the player has to perform a certain amount of repetitions of forward lunges. See Figure 3.14.a

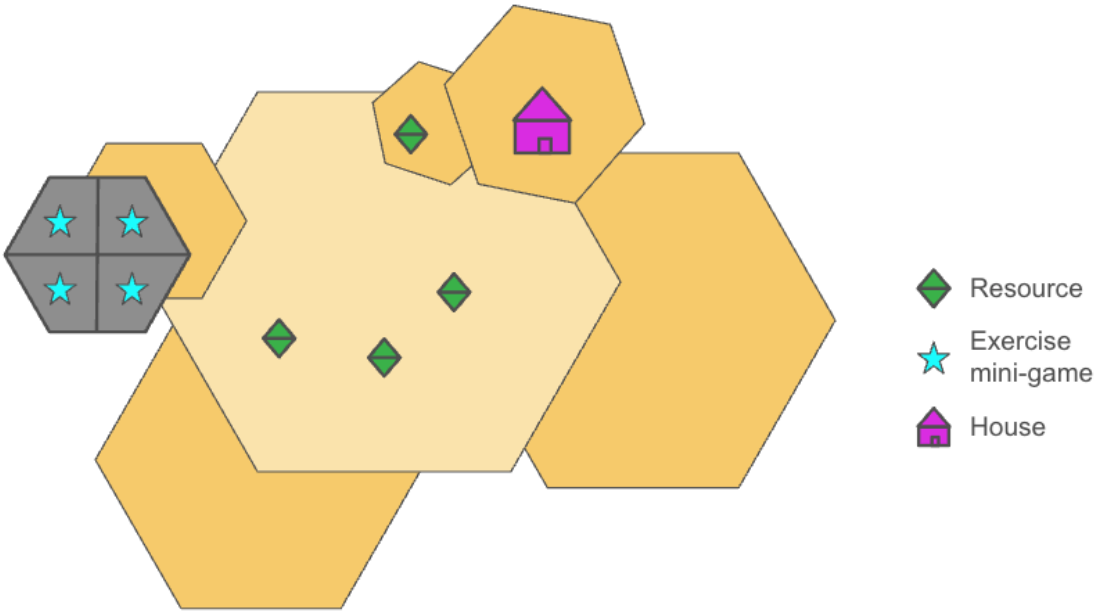


Figure 3.13: Map of virtual environment developed in Meta Horizon Worlds.

- Stone: To collect Stone, the player needs to do an amount of repetitions of lateral lunges. See Figure 3.14.b
- Sand: If the user wants to collect Sand, they need to execute a number of repetitions of squats. See Figure 3.14.c
- Brick: For the collection of Brick, the user does repetitions of heel raises. See Figure 3.14.d

When the user gets close to the resources, a sign pops up, showing the user what needs to be done and what the reward is. An example of this sign is shown in Figure 3.15. When the user touches the button that says "GO", they are teleported to the correct area to do the exercise. The exercise or mini-game area is depicted in Figure 3.13. The main idea of this area is so the users can only access the game when they find the resources, instead of freely going to do the exercises without exploration.

3.9.2 Mini-games

Following the storyboards described in Section 3.5, each mini-game was created in one section of the exercise area, or a total of four mini-games.

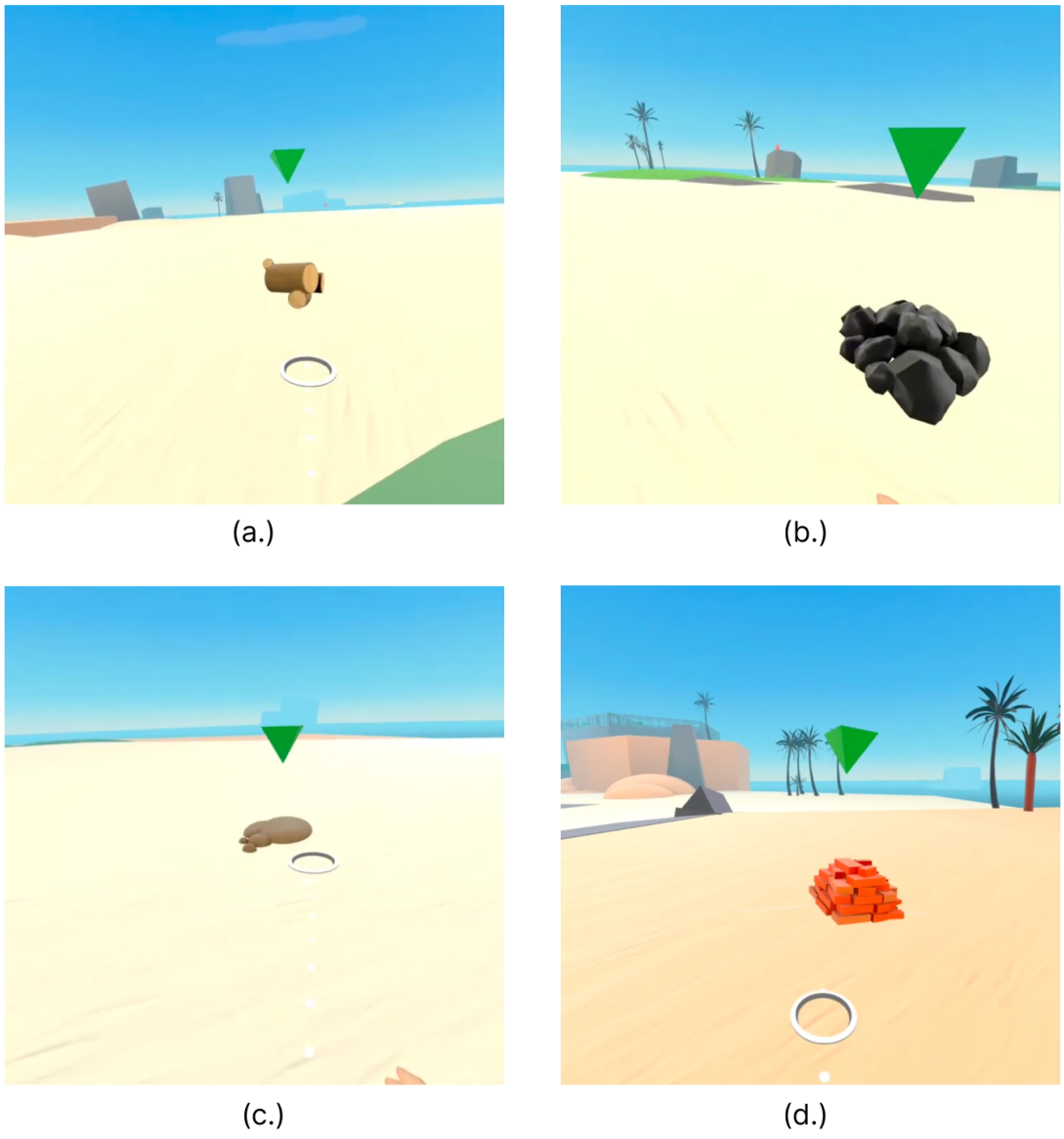


Figure 3.14: Resources in-game from the player's point of view. (a.) Wood - Forward lunges, (b.) Stone - Lateral lunges, (c.) Sand - Squats, (d.) Brick - Heel raises.



Figure 3.15: Sign that pops up to enter a mini-game.

The goal of the games is to pick up a certain resource from the floor while doing a repetition of the specified exercise (wood for forward lunges, stone for lateral lunges, sand for squats, and brick for heel raises). The repetition is valid when the user grabs the object from the floor. Once the user completes 10 repetitions, a sign pops up informing the user that 10 units of the resource have been added to the inventory.

For example, when the user gets close to a pile of wood (Figure 3.14(a)), the sign to enter the game appears (Figure 3.15). Then the user is teleported to the forward lunges game (Figure 3.16). The user will pick up the log of wood from the floor while doing forward lunges. When the user completes 10 repetitions, 10 units of wood are added to the inventory.

3.9.3 Spending Resources

After the user collects the resources by doing the necessary exercises, it is time to use this virtual currency to improve the virtual space. In this first iteration, most of the rewards and things to improve are located in the House (location is depicted in Figure 3.13). Next to the entrance of the house, there is a screen where the user can check how many resources they have available in their inventory (Figure 3.18).



Figure 3.16: Beginning of mini-game of forward lunges.

The elements to "purchase" are furniture, and each of them has a different cost in resources. An example of what the user sees while in the game is shown in Figure 3.17. If the user has enough resources in their inventory, the object will appear in the house. If the user doesn't have enough resources, a sign telling the user that they don't have enough to get it will briefly appear in front of them.

The high-fidelity prototype that was developed used a Meta Quest 3 HMD and Meta Horizons as the prototyping tool, as they are a cost-effective solution for the general public. The use of wearable sensors was discussed and tested, concluding that for this application, they are still not feasible to use by people in their homes without assistance, as they require high technical knowledge to set up for a correct reading. This chapter described the elements the player will interact with, how to make progress on the game by earning resources and how to add objects to personalise the virtual environment. The next chapter shows how the system testing was carried out.



Figure 3.17: Point of view of the user. Sign to purchase element in the game. The sign specifies the resources needed to get it.

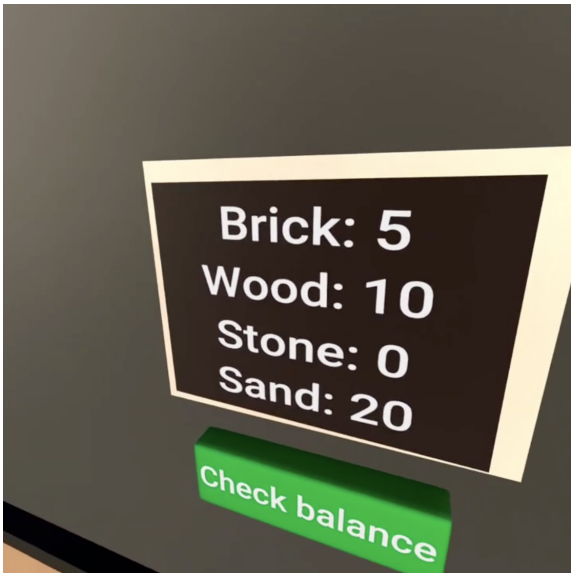


Figure 3.18: Inventory screen. The user can update the information by pressing the "Check Balance" button underneath

Chapter 4

Testing and Results of Cosy ACL

4.1 User Study Design

The feedback from users is the most important part in designing an application, especially when it comes to adherence and motivation. A user study was designed and received approval from the DCU Research Ethics Committee under reference DCUREC/2023/054.

4.1.1 Participants

Participants aged 18 years or older were invited to participate in the study. A Google form was created for people to register their interest in participating in the study. The registration form included all the details of the study and outlined the tasks to perform. The registration form was distributed by email to DCU students from the School of Health and Human Performance, GAA clubs and physiotherapy clinics located in the north side of Dublin, and audiences attending science communication events. The form was also distributed as a QR code on different information boards on the Glasnevin campus of Dublin City University.

Interested individuals were contacted by email and invited to visit the Biomechanics Lab in the School of Health and Human Performance at Dublin City University, on a specific day selected by them, according to their availability, for a period

of 1-2 hours. Upon visiting the lab, the study was explained and discussed with the participants and they were given the opportunity to ask questions before signing a consent form. 15 participants were invited to participate in the study, 10 of them were participants who have not previously gone through physical rehabilitation programmes, and the remaining 5 were participants with previous experience doing physical rehabilitation. The previously injured group includes participants who sustained the injury up to 15 years ago, their experience through rehabilitation and recovery is important to the application, as they can compare it to strategies and plans that they used when they first suffered these injuries. The non-injured participant group is used to give us a baseline to differentiate aspects of the system that need improvement. Detailed information about the virtual environment can be found in Section 3.

4.1.2 Questionnaires

During the study, participants were asked to complete the following questionnaires:

- **Simulator Sickness Questionnaire [164]:** This questionnaire helps determine whether the application creates any type of motion sickness using a HMD. The application is designed to be low-impact. Participants filled out this questionnaire before and after using the HMD.

- **HEXAD Gamification User Types Questionnaire [49]:** This questionnaire determines what type of Gamer user type each participant is. Knowing this information gives more context on the feedback the participants provided as different people have different preferences when it comes to games.

- **Feedback questionnaire (Available in Appendix B):** This questionnaire was designed based on the Game Mechanics section of the Virtual Reality Neuroscience Questionnaire [165]. Part A of this questionnaire is composed of six questions using a likert scale for participants to describe how they felt with certain elements of the experience, including questions about wearing

the headset and the sensors to evaluate whether the hardware affected the way participants performed the tasks. The six questions created also had an open space for participants to add any comment related to that question. In Part B of this questionnaire, the participants answered a four questions related to their injury, fitness level, and previous VR experience.

4.1.3 Tasks

All participants performed the same tasks. Depending on the participant, the time to complete the tasks ranged from 40-60 minutes. The experiment involved the following general steps:

- Before participants did any physical tasks, they were asked to do some stretching exercises to minimise the risk of being injured during the testing.
- Participants were introduced to the equipment: VR headset (Meta Quest 3), wearable sensors (Sony Mocopi sensors).
  - Participants are likely to have no previous experience using a VR headset. This is why the first 15-20 minutes consisted of initial training using the VR headset. A set of simple apps from the Meta Quest 3 store were used. This first interaction with the headset helped to make sure that the participants did not experience side effects like nausea and motion sickness from the use of the device and also to get them familiar with using the controllers. Before the training session, participants answered the Simulator Sickness Questionnaire, as well as after the training session.
  - For the wearable sensors, participants were instructed on how to wear them and what these devices do. The sensors were located in the following way: one sensor in each wrist, one sensor on each ankle, one sensor in the lower back, and one sensor on the head as seen in Figure 3.12.
- After the initial training, the setup with the wearable sensors and VR headset was carried out. Participants were minimally instructed on the tasks to

perform inside the virtual environment.

- The virtual environment is a space that is free for the user to explore.
- In some areas of the virtual space, the participant performed specific exercises as if they were entering a mini-game. In this prototype there are four exercises: Forward lunges, lateral lunges, squats, and heel raises. For more details about the specific exercises to perform, see Sections 3.5.3, 3.5.4, 3.5.5, and 3.5.6.
- There was no time limit for the participants inside the virtual environment, as feedback regarding adherence in the game was needed.
- At any point of the participation, the user was able to go explore the area where the reward can be purchased. For more detailed information about the rewards, check Section 3
- After the participant completed the tasks and finished exploring, the devices were taken off the participant.

4.2 Results

For this study, 20 people registered, of which 17 people fulfilled the requirements of participation. From the 17 participants contacted, two of them withdrew their participation. The remaining 15 participants completed the study and follow-up questionnaires.

In total, 10 non-injured participants and 5 previously-injured participants took part in the first iteration of the game. Table 4.1 shows the information provided by the participants during the course of the study. Of the 15 participants, only 3 had used a VR headset more regularly. 9 participants had used a VR headset once or twice, and 4 participants had never used a VR headset before this study.

All participants answered the questionnaires described in Section 4.1.2. None of the participants showed symptoms of motion sickness caused by the application.

The game was designed as a slow-paced game play, which helps to avoid motion sickness within the virtual environment.

4.3 HEXAD User Gamer Types

All the participants answered the HEXAD user gamer types questionnaire. This information was used to guide the next iteration about elements in the game play that should be added or removed. The results from this questionnaire also gives more qualitative information about the rehabilitation gaming experience when reading the feedback from the participants.

4.3.1 General Results

Table 4.2 shows the results of the HEXAD questionnaire in all participants of the first iteration of the game. When there was a tie in the results, the updated HEXAD-12 [166] was used to obtain the dominant user gamer type of the participant.

Figure 4.1 shows a summary of the dominant gamer types for the 15 participants that were part of the study. This includes non-injured and previously-injured participants. Almost 50% of the participants are predominantly Free Spirits (46.7%), followed by Philanthropists and Players with 20%. Lastly, we had one participant with an Achiever gamer type, and one participant with a dominant Socialiser gamer type. This does not mean that participants will reject certain game elements just because it does not fit with their gamer type, but rather that there are certain game elements that they will be more interested in interacting with than others.

4.3.2 Non-injured Participants

Table 4.3 shows the results of the HEXAD user type questionnaire only from the non-injured participants.

In the case of the non-injured participants for this study, 6 of them present a dominant Free spirit gamer type, followed by 2 participants having a dominant Phi-

Participant	VR literacy	Fitness level	ACL injury	Time since ACLR
1	High	Occasionally play sports or attend gym	No	N/A
2	Low	Occasionally play sports or attend gym	Yes	6.5 years
3	High	Occasionally play sports or attend gym	No	N/A
4	High	Occasionally play sports or attend gym	No	N/A
5	Low	Occasionally play sports or attend gym	No	N/A
6	Medium	Amateur athlete	No	N/A
7	Medium	Amateur athlete	Yes	4 years, 1 year
8	Medium	Occasionally play sports or attend gym	Yes	7 years
9	Medium	Occasionally play sports or attend gym	No	N/A
10	Medium	Occasionally play sports or attend gym	No	N/A
11	Medium	Amateur athlete	Yes	8 months
12	Low	Occasionally play sports or attend gym	No	N/A
13	Medium	Occasionally play sports or attend gym	No	N/A
14	Low	Occasionally play sports or attend gym	No	N/A
15	Medium	Amateur athlete	Yes	15 years, 4 years

Table 4.1: Information of participants in the study. Low VR literacy: never worn a VR headset, Medium VR literacy: Have tried VR once or twice before, High VR literacy: Have used VR regularly or own their own headset.

Participant	Dominant user type	2nd user type	3rd user type	4th user type	5th user type	6th user type
1	F	R	A	P	S	D
2	P	S	F	R	A	D
3	F	P	R	A	S	D
4	F	R	P	A	S	D
5	P	A	S	R	F	D
6	R	P	S	A	F	D
7	R	A	F	P	S	D
8	F	A	R	P	S	D
9	S	P	R	A	F	D
10	F	R	A	P	S	D
11	A	R	P	F	S	D
12	F	A	R	P	S	D
13	F	R	P	S	A	D
14	P	F	A	D	S	R
15	R	F	A	P	S	D

Table 4.2: Dominance of gamer user types on participants according to the HEXAD gamer user type questionnaire. P: Philanthropist, S: Socialiser, F: Free spirit, A: Achiever, R: Player, D: Disruptor.

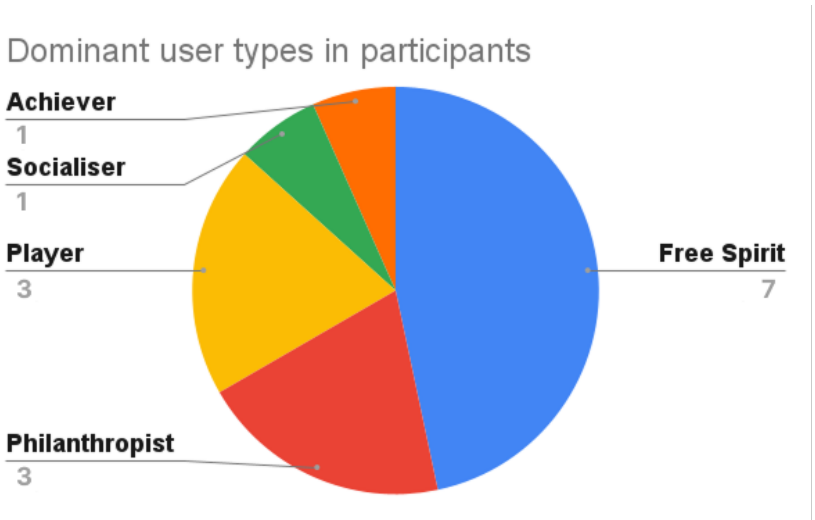


Figure 4.1: Dominant HEXAD gamer type for the 15 participants in the study (Non-injured and previously-injured).

Participant	Dominant user type	2nd user type	3rd user type	4th user type	5th user type	6th user type
1	F	R	A	P	S	D
3	F	P	R	A	S	D
4	F	R	P	A	S	D
5	P	A	S	R	F	D
6	R	P	S	A	F	D
9	S	P	R	A	F	D
10	F	R	A	P	S	D
12	F	A	R	P	S	D
13	F	R	P	S	A	D
14	P	F	A	D	S	R

Table 4.3: Dominance of gamer user types on non-injured participants according to the HEXAD gamer user type questionnaire. P: Philanthropist, S: Socialiser, F: Free spirit, A: Achiever, R: Player, D: Disruptor.

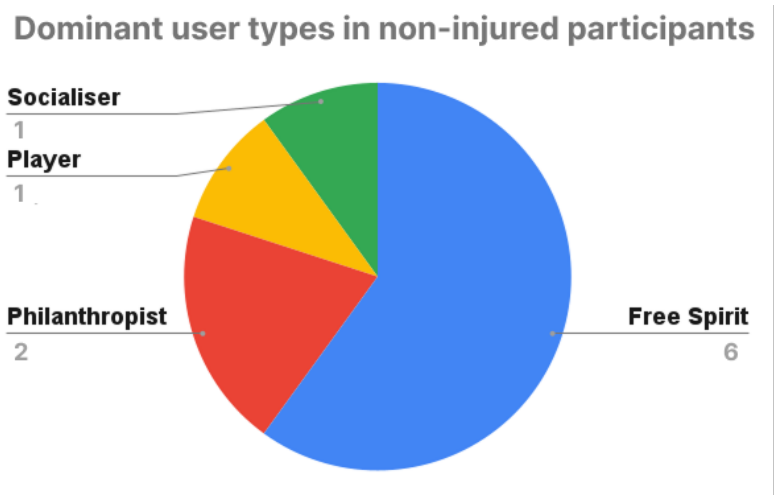


Figure 4.2: Dominant HEXAD gamer type for the 10 non-injured participants in the study.

Participant	Dominant user type	2nd user type	3rd user type	4th user type	5th user type	6th user type
2	P	S	F	R	A	D
7	R	A	F	P	S	D
8	F	A	R	P	S	D
11	P	A	R	F	S	D
15	R	F	A	P	S	D

Table 4.4: Dominance of gamer user types on previously-injured participants according to the HEXAD gamer user type questionnaire. P: Philanthropist, S: Socialiser, F: Free spirit, A: Achiever, R: Player, D: Disruptor.

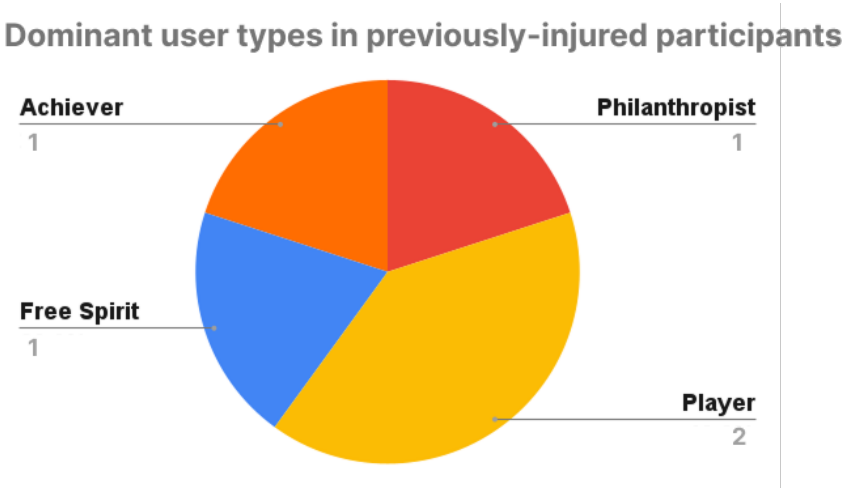


Figure 4.3: Dominant HEXAD gamer type for the 5 previously-injured participants in the study.

lanthropist gamer type. The least common gamer types were Players and Socialisers with only 1 participant each.

4.3.3 Previously-injured Participants

Table 4.4 shows the results of the HEXAD user type questionnaire only from the participants that have had a knee injury.

From the 5 participants in the study with a knee injury, 2 of them present a dominant Player gamer type, followed by 3 participants with a different gamer type each (Free Spirit, Achiever, Philanthropist).

4.4 Feedback on First Iteration

After the participants played the game, they were asked to answer a questionnaire with questions related to comfort and characteristics of the game (See Annex B for the questionnaire). The questions relate to comfort wearing the headset (Q1), Ease of movement and confidence (Q2 to Q4), and Engagement (Q5 and Q6). The answers were given in a Likert scale and they also had space to write more openly in each question. Table 4.5 shows the responses that the participants provided in the questionnaire.

From the participants' responses to the Feedback Questionnaire, a thematic analysis was performed to identify common themes within each topic of the questionnaire. The themes are divided into six: Comfort (Q1), Stress (Q2), Movement confidence (Q3), Ease of movement (Q4), Engagement (Q5), and Likelihood of adherence (Q6). Within these six themes, sub-themes were found and analysed. This section shows the interpretation of the participant's feedback.

4.4.1 Comfort Wearing the Headset

This question aimed to check if the headset would impede the participants' movements during the execution of the exercises and overall feeling while using the application.

Figure 4.4 shows the responses of the participants to this question. All participants reported feeling comfortable or very comfortable wearing the headset, and there is no particular difference between non-injured and previously-injured participants. The Meta Quest 3, as mentioned in Section 3.8.1, has a more ergonomic design than the previous models, providing more comfort while using it.

Participant 7 mentioned the following: *"No discomfort. Just got a bit sweaty around the eyes and face"*. For hygiene purposes, the silicone facial covering was used for all tests as it is easy to clean with an antibacterial wipe after each use. The default headset cover is made of fabric, which could absorb sweat moisture, making it more difficult to clean and use with several people.

Participant	Q1: Comfort using headset	Q2: Stress during task	Q3: Confidence in movement	Q4: Ease of movement with headset	Q5: Feeling of engagement	Q6: Likelihood of using the system
1	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
2	6 (Comfortable)	1 (Very relaxed)	7 (Very confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
3	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
4	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	4 (Neutral)	7 (Very engaged)	7 (Very likely)
5	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	1 (Very unlikely)
6	6 (Comfortable)	2 (Relaxed)	5 (Somewhat confident)	5 (Somewhat easy)	6 (Engaged)	7 (Very likely)
7	6 (Comfortable)	1 (Very relaxed)	7 (Very confident)	6 (Easy)	7 (Very engaged)	6 (Likely)
8	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
9	6 (Comfortable)	2 (Relaxed)	5 (Somewhat confident)	6 (Easy)	6 (Engaged)	5 (Somewhat likely)
10	7 (Very comfortable)	2 (Relaxed)	7 (Very confident)	6 (Easy)	7 (Very engaged)	7 (Very likely)
11	7 (Very comfortable)	1 (Very relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
12	6 (Comfortable)	1 (Very relaxed)	6 (Confident)	6 (Easy)	7 (Very engaged)	7 (Very likely)
13	7 (Very comfortable)	1 (Very relaxed)	5 (Somewhat confident)	6 (Easy)	7 (Very engaged)	7 (Very likely)
14	7 (Very comfortable)	1 (Very relaxed)	7 (Very confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)
15	6 (Comfortable)	2 (Relaxed)	6 (Confident)	7 (Very easy)	7 (Very engaged)	7 (Very likely)

Table 4.5: Likert scale answers to the feedback questionnaire by the participants.

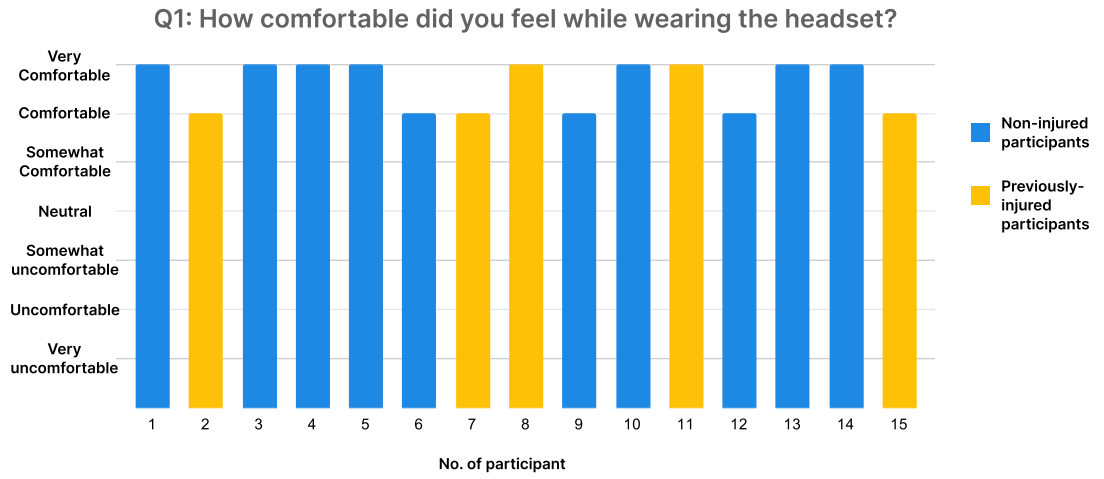


Figure 4.4: Responses from participants to Question 1 of the questionnaire (*"How comfortable did you feel while wearing the headset?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

4.4.2 Stress while Playing

The second question presented to the participants asked them to evaluate if they felt any stress or nervousness while playing the game and doing the exercises. As seen in Figure 4.5, all participants felt relaxed and very relaxed while playing the game. From the additional comments given by the participants, music and aesthetics of the virtual environment helped to create this feeling of relaxation.

From participant 3:

> *"The sound effects helped to maintain immersion, perfectly matching the beach environment"*

From participant 8:

> *"I think the music and the sounds helps creating a relaxing environment"*

From participant 15:

> *"Nice environment, fun to try the activities"*

For other participants, like participant 9, who had only used a VR headset once or twice before, they needed an initial period to get accustomed to the controllers, but after a few minutes, they relaxed and played the game as normal.

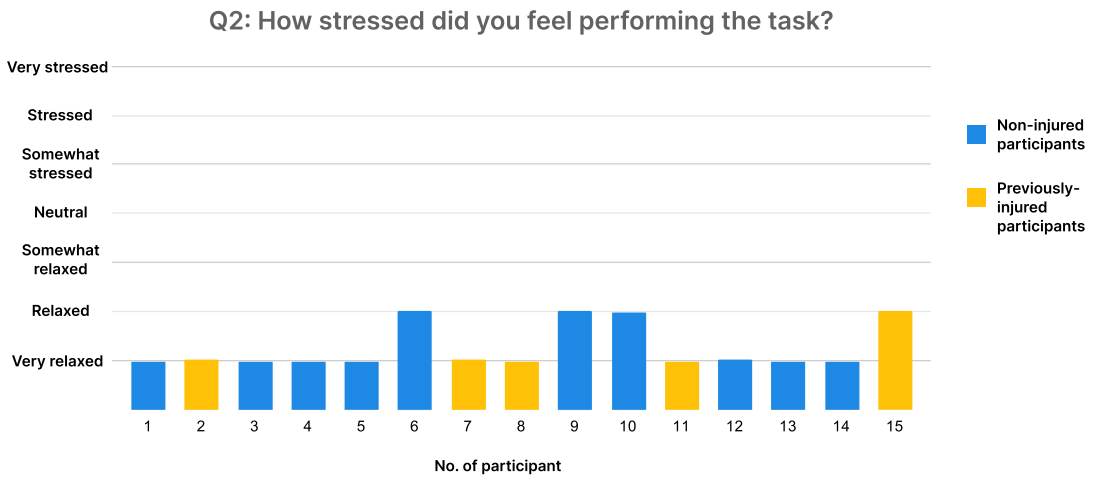


Figure 4.5: Responses from participants to Question 2 of the questionnaire (*"How stressed did you feel performing the task?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

The additional feedback on Question 2 from participant 9 was the following:

> *"Initially I felt stressed about the equipment and whether I'd make a fool of myself by not using it correctly, but then as I got more used to it, I relaxed and with time, I started to notice things in the environment which I'd initially overlooked due to my worry."*

In addition to novelty, users can feel some stress related to using a new technology that is very different from what they have used before. But, as said by the participant, after a short while, these feelings tend to fade away.

4.4.3 Confidence in the Movements

The third question was about how confident the participants felt in their movements, especially while doing the exercises. All participants that have had sustained an injury reported feeling confident and very confident (see Figure 4.6). Three participants reported feeling somewhat confident, further feedback showed that this result improved after a few repetitions, but there is still a need for some guidance in performing the exercise and some feedback.

Two of the previously-injured participants (Participants 7, 8, and 11) talk and

mention the need for some feedback in order to be sure that the movement was correct. This tendency may be due to the loss of proprioception after this type of injury, making them more dependent on visual feedback for certain movements [167, 168]. The use of these virtual scenarios could also help train patients in recovering their proprioception after ACLR surgery, by reducing the level of visual feedback available to them.

From participant 7:

"Very confident although would like to have some form of proprioception"

From participant 8:

"I needed a couple of minutes to get used to the movements, after that it was really easy."

From participant 11:

"I didn't really have a way to make sure my leg movement was correct"

Two participants from the non-injured group also mentioned feeling unsure about their movements at the beginning, but also manifested that after some practice they felt more confident performing the exercises.

From participant 5:

"At the start a 6, but then 7 once used to it"

From participant 9:

"I wasn't certain whether I was doing the exercises correctly or not."

Other comments, made by participant 3 and participant 15, are more related to bugs in the prototype, which made the objects change position a little bit while doing the exercises, but overall that did not affect their performance in the application:

From participant 3:

"Somewhat confident at the start of the exercise, since the resources move a little bit. After a while, you get the hang of it. By the 4th repetition, I was very confident."

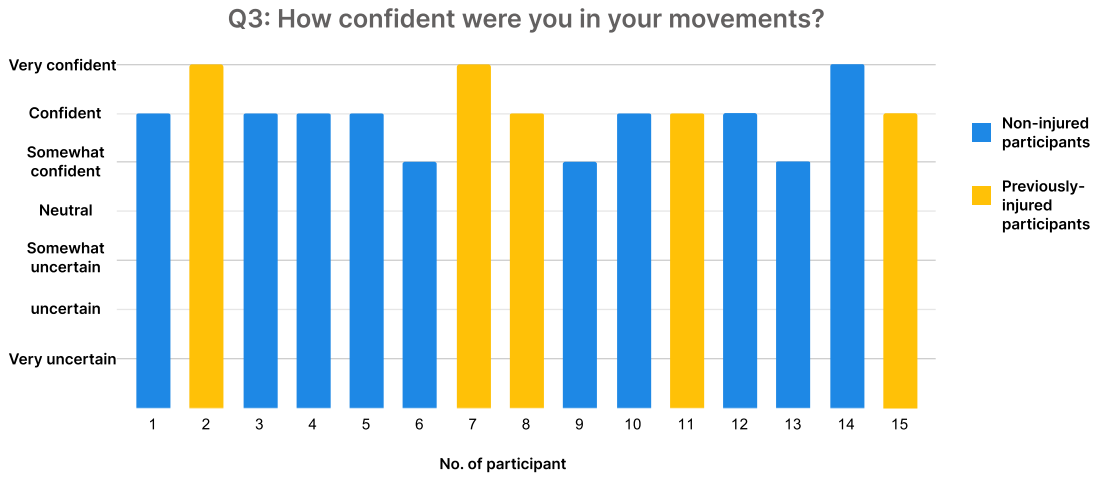


Figure 4.6: Responses from participants to Question 3 of the questionnaire (*"How confident were you in your movements?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

From participant 15:

> *"Some changes in depth created confusion that allowed for doubt"*

4.4.4 Ease of Movement

This question was about general movement in the physical space where the participants were playing and if there was any difficulty while wearing the headset. Figure 4.7 shows that most participants felt that it was easy and very easy to move around. Two participants reported feeling neutral about it (Participant 4) and that it was somewhat easy (Participant 6). Participant 4 did not share more feedback that explains their response to this question, but Participant 6 expressed the following: *"Felt slightly confined in a small space."*. This participant was worried about crashing against a real wall while in the game, even though the testing scenario had plenty of space. This could be due to not being used to using VR, as the participant reported having used it only once or twice before. Also, as seen in Section 3.9.2, the player is teleported to a closed space to do the exercises, and that could have contributed to that feeling of being in a small space.

From participant 7:

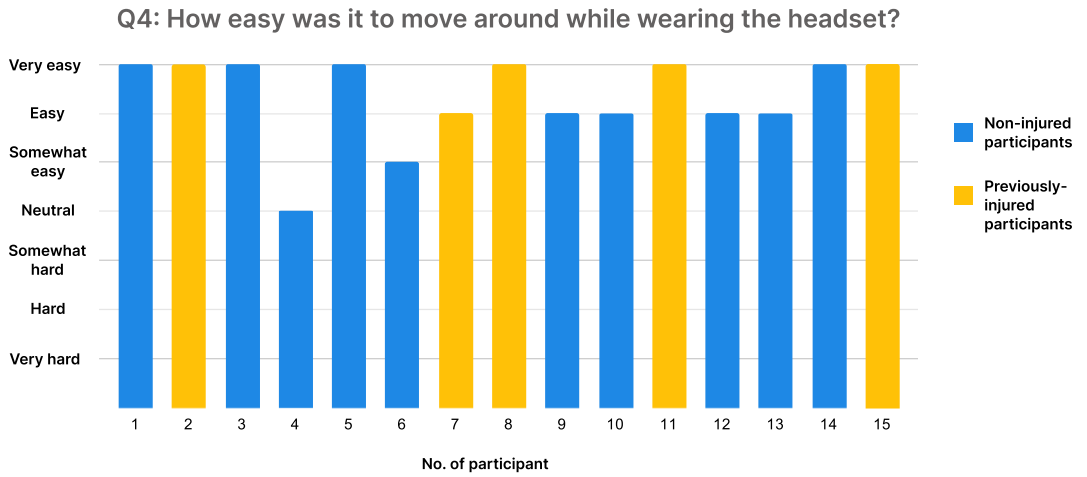


Figure 4.7: Responses from participants to Question 4 of the questionnaire (*"How easy was it to move around while wearing the headset?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

"Easy, but orientation in the room was difficult"

From participant 9:

"I found it very easy and I didn't even notice that I was wearing it"

From participant 11:

"It was light and intuitive to me"

From participant 15:

"Headset is heavy but still easy to navigate"

4.4.5 Engagement in the Game

This question was aimed to check if the participants felt engaged during the game, if they thought the gameplay was motivating, and whether they had fun or not. Figure 4.8, shows that all participants reported feeling Very engaged and Engaged during the test. There was very positive feedback related to the rewards and game mechanics. Almost all participants stayed longer in the application just to explore, even though they had already completed the tasks.

From participant 3:

"The rewards that you can buy are motivating. I was exercising while thinking that I'd be able to build furniture with the resources I had been collecting."

From participant 4:

"I liked it a lot. The ambiance was very relaxing and I liked to explore and walk around. I just missed a bit of context, I understood we were getting resources to build furniture for the house, but I would like a bit more of narrative even if it is simple."

From participant 9:

"I felt very engaged while doing the exercises and I wanted to do more of each one. Once there were no further exercises available, I was disappointed."

From participant 11:

"It was fun"

From participant 12:

"The thing I liked the most were the rewards"

From the comments above, although participants were very engaged, and as participant 4 remarked, this prototype lacked the narrative that would provide the game with more context. It was also observed that half of the participants tried to do the exercises a second time to get more resources in the same session, showing that it is necessary to limit the tasks each day to avoid overexercising. The prototype tested would only allow one set of exercises per session.

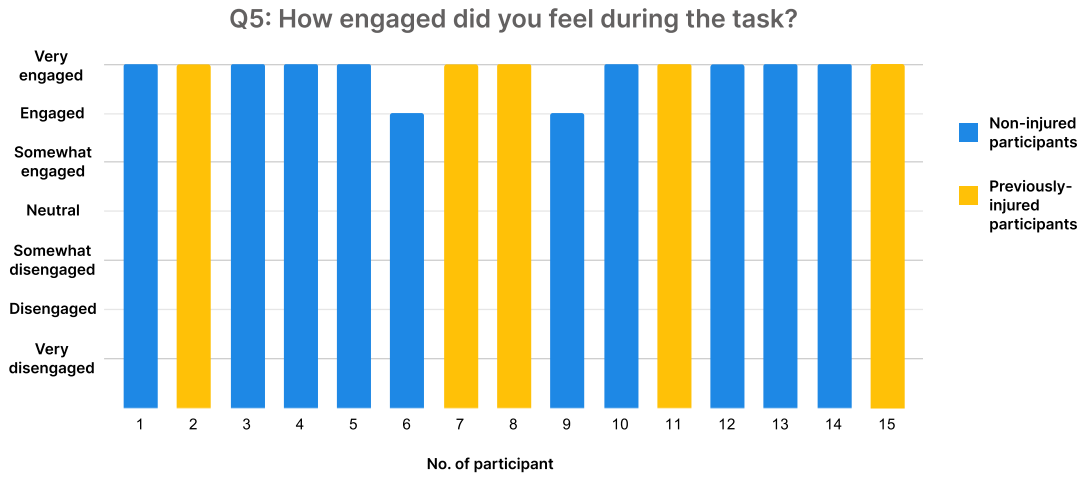


Figure 4.8: Responses from participants to Question 5 of the questionnaire (*"How engaged did you feel during the task?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

4.4.6 Likelihood to Keep Using the Game

The last question presented to the participants asked them if they would use this type of game to do their daily exercises. 12 out of the 15 participants reported that it would be very likely for them to use this kind of game for their exercises, as seen in Figure 4.9.

Participant 9 reported that it would be somewhat likely for them to use it, but they needed a social component to be really motivated, as she expressed in their comments: *"Social/Team dimension would be important for me to motivate me to come back. The prizes alone in a solitary playing of the game wouldn't invite me to come back"*. This participant in particular was the only one with a Socialiser gamer user type, showing that certain characteristics are more important than others depending on their dominant gamer user type. This prototype did not contemplate a social component given that the main goal for this game is to appeal to Free Spirits.

From the participants' answers, one participant reported that it would be very unlikely for them to use this type of game (Participant 5). This participant gave the following feedback regarding this answer: *"If I was injured or doing rehab then I would definitely do it. However I enjoy going to the gym so I don't need a headset*

to do daily tasks.".

It can also be observed that the participants who have had an ACL injury commented on how useful a game like this would have been when they were doing their rehabilitation programme:

From participant 7:

> *"Really enjoyable and the restriction on the amount of daily exercise you can achieve in the game makes you want to return the next day to play"*

From participant 8:

> *"It would be useful to find the motivation for daily exercises. Especially during the rehabilitation process."*

From participant 11:

> *"I enjoyed it immensely, I could see myself using it a lot, especially early on in my recovery."*

From participant 15:

> *"Definitely would do daily"*

Some of the non-injured participants commented on how this application would help them get more active and do more exercise:

From participant 4:

> *"Usually gym or home exercises can be boring, so I like it because it's fun and motivational."*

From participant 6:

> *"Very likely, works very well and rewards help to motivate"*

This feedback from the participants also shows that this type of game could also be expanded to improve fitness level in more sedentary people, as well as for other types of injuries.

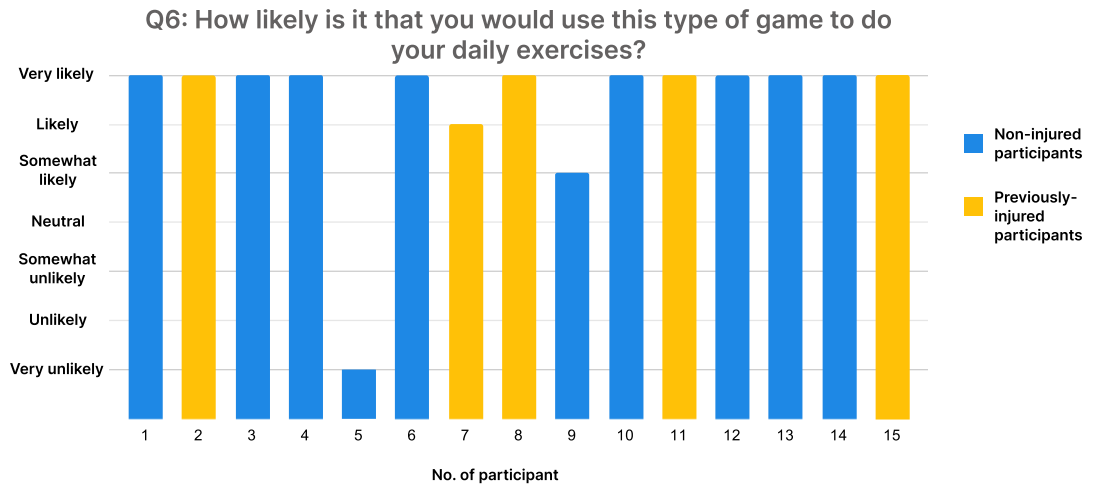


Figure 4.9: Responses from participants to Question 6 of the questionnaire (*"How likely is it that you would use this type of game to do your daily exercises?"*). Participants in yellow have had an ACL injury, and the participants in blue have not had an injury.

4.4.7 Other Feedback

Participants also had a space at the end of the questionnaire to write any other feedback or comment they had about the game.

Some participants highlighted the usefulness of the system once more:

> Participant 1: *"The game was very motivating. I have previously found PT exercises to be very boring and would eventually dread them and stop altogether. This game made me want to do them again"*

> Participant 7: *"Great system, can really see the application and how it can work to motivate the user."*

> Participant 12: *"I hope there is more exercises. I think it would help to have a good time while exercising and help people with some injuries"*

Other participants gave more specific feedback in terms of the elements that would improve the experience:

> Participant 3: *"I would feel more engaged with the in-game rewards, going towards building the house."*



Figure 4.10: Word cloud representing the responses of the participants after using *Cosy ACL*.

> Participant 4: *"I would change the colour of the house to be cozier. Maybe a beige color and put some windows to make it clearer."*
>
> Participant 13: *"Put counters about how many exercises are doing at the moment"*
>
> Participant 15: *"More activities, A mirror or avatar doing the exercises, Cosier location for exercises that the current "cage"*

4.5 Functional Movement Assessment

During the completion of the tasks, some participants commented on the fact that after 3 or 4 repetitions, they were more sure about their movements than at the beginning (See Section 4.4.3). In Section 3.8.2, some of the difficulties in testing the system along with the Sony Mocopi sensors were described. Given these difficulties, in which the sensors were not connecting correctly, it was not possible to take measurements of the participants while playing the game in order to assess the movements. In cases where the connection was successful, the data recorded was

corrupted and therefore, unusable. Given this situation, participants were asked to stay longer in the biomechanics lab to record them on video while doing the forward lunges exercises. Only participant 15 agreed and was recorded on video in two scenarios: wearing the VR headset, and not wearing the headset. The software Kinovea was used to measure the angles of the knee for the forward lunges exercise. Kinovea is an open-source video annotation tool specifically designed for sport analysis [169]. Various studies have determined that Kinovea is a reliable tool to measure angles during exercise and clinical settings [170, 171, 172, 173, 174, 175, 176, 177], showing a Minimal Detectable Change (MDC) between 1.3°and 11.2°across studies. These studies also show a Standard Error of Measurement (SEM) between 0.5°and 1.5°.

Table 4.6 shows a comparison of the knee angles in the final position of the lunge of one previously-injured participant with and without wearing the VR headset, after some initial practive using the VR controllers. In this position, the knee angle should ideally be approximately 90 degrees to be considered a correct lunge. It is visible that the first 2 repetitions while wearing the headset were difficult for the participant, given that the back leg in these repetitions is around 73°. But also, on the third repetition both front and back leg have better angles, which corresponds to the feedback given by the participant at the end of the test that he felt more comfortable in his movements by the third or fourth repetition.

Left Leg

A two-tailed paired sample t-test was performed on these measurements on the following hypotheses:

$H_0 : \mu_1 = \mu_2$ (the two population means are equal)

$H_1 : \mu_1 \neq \mu_2$ (the two population means are not equal)

The calculations were made by comparing the knee angles of the left leg, which in this case also corresponds to the previously-injured knee, in the last position of the forward lunge. The data were plotted in Figure 4.11. The goal of this test is to check whether there is any significant difference in performing the exercise while

	Knee angles with headset		**Knee angles without headset**	
Repetition	**Left**	**Right**	**Left**	**Right**
1 (RF)	73.2°	87.3°	94.6°	84.3°
2 (LF)	82.7°	73.6°	80.1°	87.5°
3 (RF)	84.3°	91.3°	86.8°	85.3°
4 (LF)	90.8°	78.9°	94.9°	84.9°
5 (RF)	76.2°	86.4°	97.6°	95.1°
6 (LF)	89.8°	81.5°	93.8°	89.6°
7 (RF)	79.4°	89.7°	87.2°	87.2°
8 (LF)	89.7°	80.5°	87.4°	81.8°
9 (RF)	78.3°	86.6°	92.6°	96.6°
10 (LF)	91.3°	70.2°	86.9°	82.3°

Table 4.6: Knee angles of a previously-injured participant when in the last position of a forward lunge while using the headset and without the headset. The participant took turns in bringing each leg forward, starting with the right leg. RF: Right leg in the front, LF: Left leg in the front.

wearing a VR headset or not.

The p-value for the left knee angles is 0.05517, with this result we reject the null hypothesis, and we can conclude that there is no significant difference in the knee angle measurements while wearing a VR headset compared to not wearing a headset.

Right Leg

The same two-tailed paired sample t-test was performed on these measurements on the following hypotheses:

$H_0 : \mu_1 = \mu_2$ (the two population means are equal)

$H_1 : \mu_1 \neq \mu_2$ (the two population means are not equal)

The calculations were made by comparing the knee angles of the right leg, which is the leg with no injury, in the last position of the forward lunge. The data were plotted in Figure 4.12. The goal of this test is to check whether there is any significant difference in performing the exercise while wearing a VR headset or not.

The p-value for the right knee angles is 0.05409, which rejects the null hypothesis as well. This result means that there are no significant differences in the knee angles of the right knee while performing a forward lunge while wearing a VR headset or

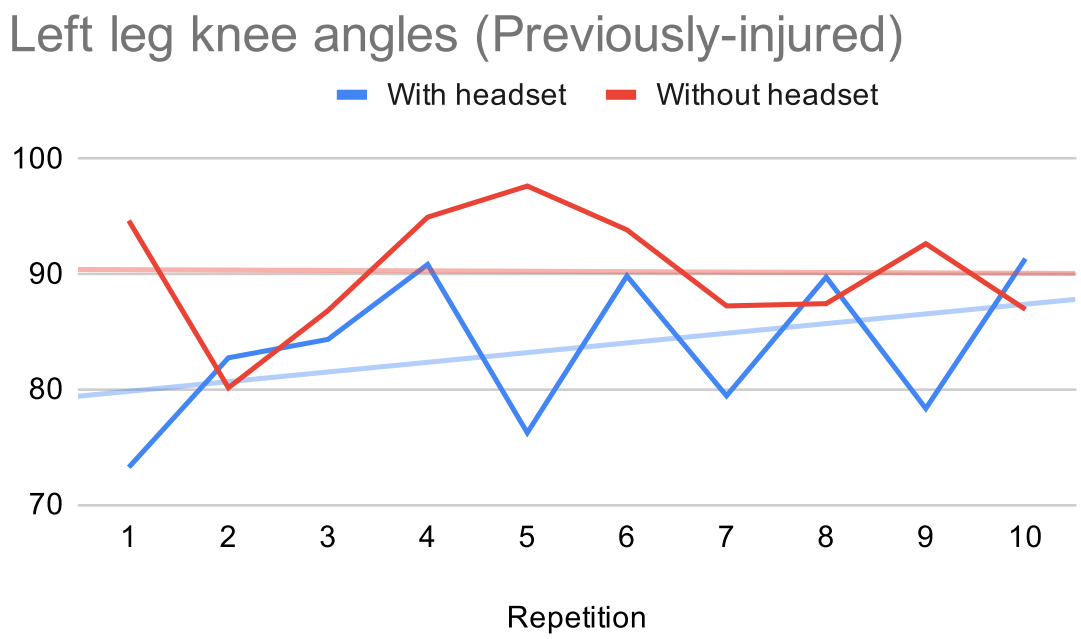


Figure 4.11: Left knee angles measured with Kinovea on Participant 15. The measurements correspond to the participant's previously-injured knee.

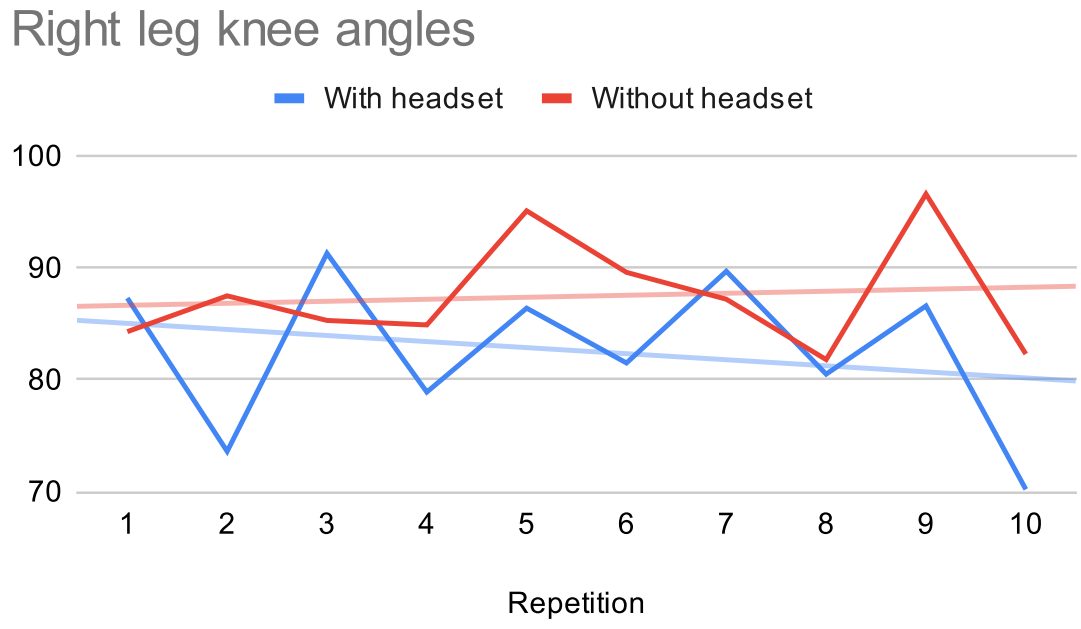


Figure 4.12: Right knee angles measured with Kinovea on Participant 15. The measurements correspond to the participant's non-injured knee.

not.

There are still slight differences in the knee angles, but this could be due to the participant getting physically tired, as the lunges done without the headset were performed first, and those wearing the headset were done during the use of the game. Looking at Figure 4.11,which corresponds to the previously-injured leg of the participant, it is observed that when the participant was not wearing the VR headset, the trend line remains very consistent around 90°. For the case of the participant wearing the VR headset, the trend line starts at around 80°, but by the end of the repetitions it is very close to the expected 90°. These data supports the later comments made by the participant, and highlights that with practice, the users can improve the performance of the exercise without the use of visual feedback.

Figure 4.13 shows the 10 repetitions made by the participant while wearing the headset, compared to the ones made without the headset. For the first two repetitions using the headset, the participant shows a tendency to put his front leg too close to the back leg, affecting the final form of the lunge. Starting from repetition 3, a better form is visible as the participant gets used to the virtual environment and the inability to see his own legs. In both cases (with and without the headset), the participant's knee was in the wrong position on the first 2 repetitions, as the front knee cannot be more forward than the foot [178], but then the position improves. Another noticeable difference between the two scenarios is that the participant keeps his head straight up when he is not wearing the headset. This difference is due to the game mechanics of the VR game, in which the participant is grabbing an object from the floor while doing the lunge, causing the participant's head to lean forward to see the object he needs to grab. Ideally, the head should remain aligned with the spine and the person looking forward. This observation should be taken into account for a future design to improve in this aspect.

With this analysis, it is concluded that for this subject the use of a VR headset does not significantly affect the performance of the forward lunge exercise. Even though there is no visual feedback of the position of the legs while in the virtual

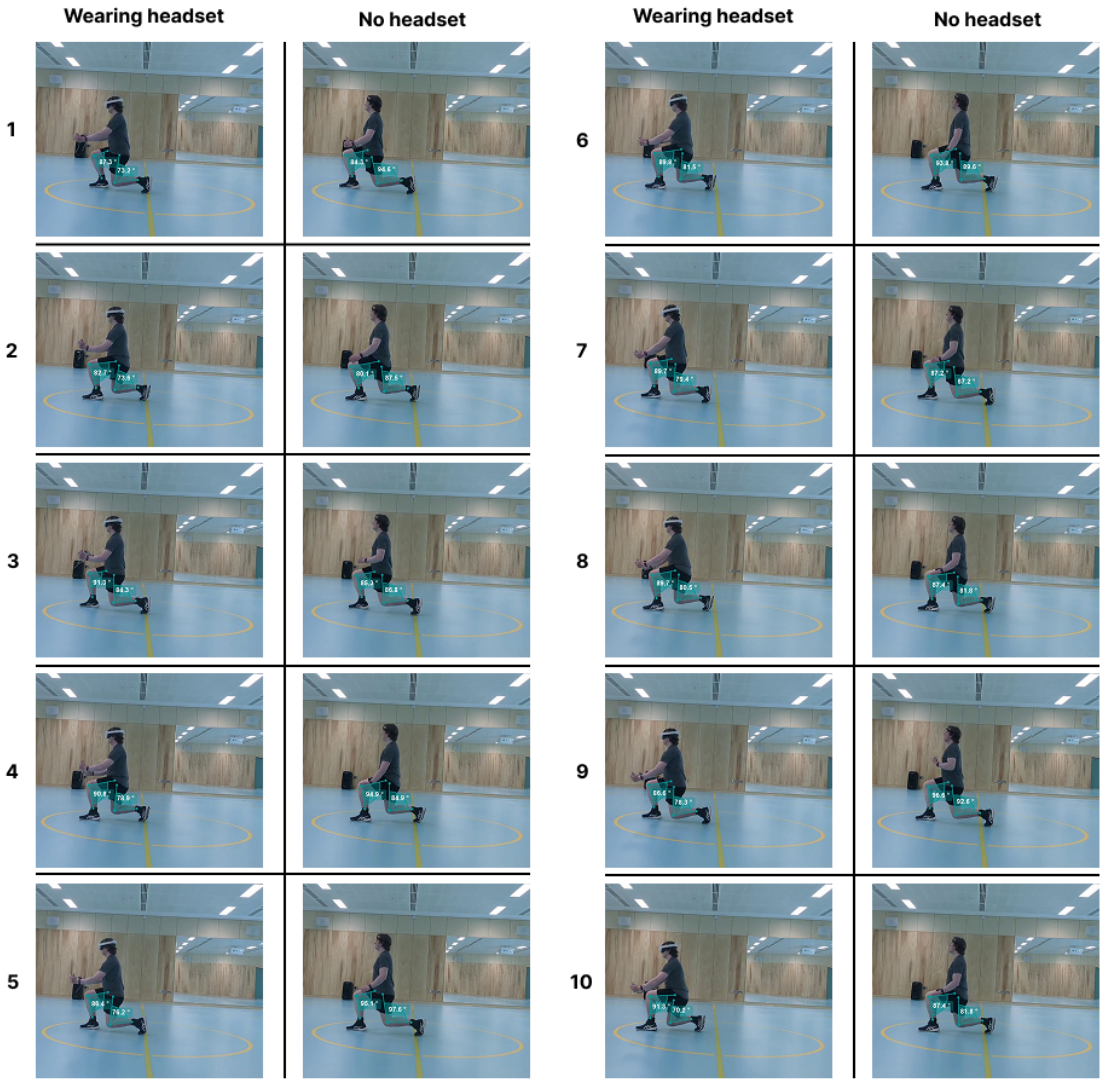


Figure 4.13: Previously-injured participant performing forward lunges while wearing the headset and without the headset. 10 repetitions are shown.

environment, the participants focused and got used to this scenario in a few repetitions. This analysis also helps answer RQ1 by showing that video recordings, along with the Kinovea software, can be a useful tool for the measurement of the patient's movement with an easier set up than wearable sensors.

4.6 Observations During Testing

All participants were very interested in exploring the virtual island even after completing the tasks. For some of the participants, this can be due to the novelty of the environment and the technology, given that most of the participants had never used VR before.

Three of the participants that reported using VR regularly also stayed longer in the environment and later commented that they wanted to find more "Easter eggs" around it. For the next study, a longer time playing the demo is needed, to observe the time spent in the game during several days, allowing to check if the novelty wears off after a few days and why.

The results of this study showed positive feedback, participants highlighted the novelty of this kind of game and suggested a few features to include in the future:

- Some background information about what to do when starting the game
- Doing the exercises somewhere else, as the participants felt like they were in a "cage"
- Changing the heel raises exercise, as it was confusing that a brick was floating in the air
- Some feedback on how many repetitions have been done, so they know how many they have left to do
- To add more spaces to explore

In the next Section, a second version of *Cosy ACL* is described, where the improvements suggested by the participants of this study were included.

4.7 Development of Cosy ACL V2

The first version of *Cosy ACL* was well received among the participants who tested the prototype, but the feedback received also provided information on the improvements that need to be implemented. This chapter describes the features added based on the feedback from the user study.

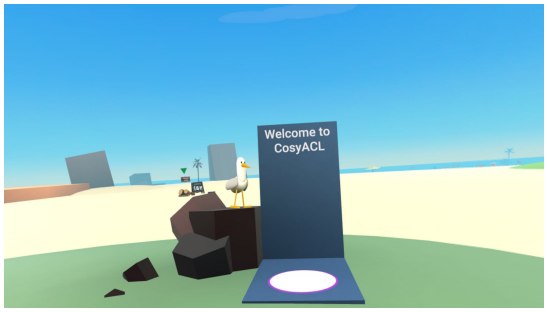
4.8 Improvements Implemented in Second Iteration

From the feedback provided by the users, improvements were made for a second iteration of the game. The following features were added to this second version:

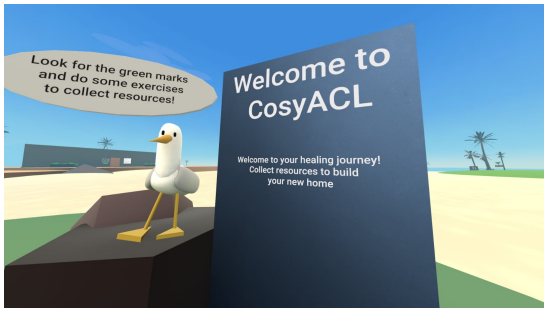
1. An information point was added.
2. During each mini-game, the amount of repetitions done is updated in real time, so the user knows how many repetitions they have done.
3. An image of the exercise to perform is shown for better guidance.
4. Changed aesthetics and locations where the games are performed.
5. The object to reach for when doing heel raises was changed.
6. A challenge was added to unlock another section of the island.

4.8.1 Information Point

Some participants indicated that some context at the beginning would help to know what to do first. In the second iteration of the application, an information point was added so that the users can walk to it and get some basic instructions regarding what to do on the island, as shown in Figure 4.14.



(a) Information point when entering the virtual world.



(b) Information displayed when the user enters the appropriate area.

Figure 4.14: Comparison between the first and second version of the application when beginning the forward lunges exercise.



(a)



(b)

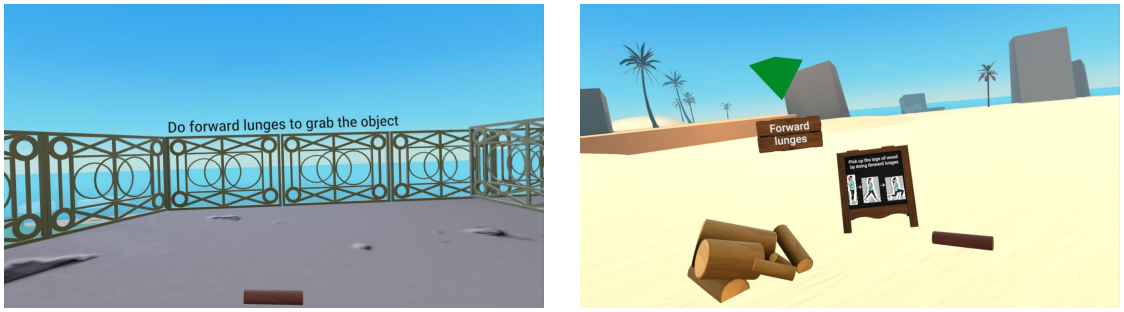
Figure 4.15: Pop-ups that the player sees that serve as progress feedback during the performance of the exercise. (a) Pop-up showing the player that they have completed 9 repetitions of the lateral lunges exercise. (b) Pop-up showing the user that the exercise has been completed.

4.8.2 Feedback on Repetitions

Each time a user completes a repetition of the exercise, a pop-up appears in front of them with the number of repetitions they have done so far, as illustrated in Figure 4.15. Once they reach 10 repetitions, the user is informed that the exercise is complete and that they have collected the intended resource (Figure 4.15b).

4.8.3 Guidance for Exercises and Relocation of Exercises

Figure 4.16 shows a comparison between the first and second iteration of the application when starting the exercise of forward lunges. In the first version, users were



(a) Version 1 (b) Version 2

Figure 4.16: Comparison between the first and second version of the application when beginning the forward lunges exercise.

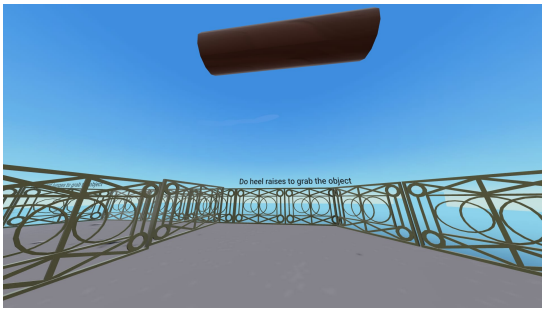
teleported to a different space in order to perform the exercises (Figure 4.16a). Some participants highlighted that the openness they felt in the island got lost when they reached this part, given that the space had fences and made them feel like they were in a cage. For the second version (Figure 4.16b), instead of teleporting the users to a different location, the exercise was integrated into the island setting, making the exercises more straightforward to complete. Also, more detailed instructions about how to do the exercise were added to give more guidance to the user. This change came from observations made during the first iteration, in which most participants did not know what exercise to do because they did not know them by name.

4.8.4 Heel Raises Exercise Update

In the first iteration of the application, the heel raises exercise did not match the theme of the island very well, and the user was asked to reach for a floating log in the air (Figures 4.17a and 4.17b) to collect bricks for the house. Many participants made comments about this and wondered if there was a bug in the game at first. For this reason the interactions for this exercise was adapted in order to make it fit better with the surroundings. For the second iteration, the user is asked to reach for coconuts in a palm tree while doing the heel raises exercise (Figure 4.17c and 4.17d).



(a) Version 1 of Heel Raises: Before starting the exercise.



(b) Version 1 of Heel Raises: Starting the exercise.



(c) Version 2 of Heel Raises: Before starting exercise.



(d) Version 2 of Heel Raises: Starting the exercise.

Figure 4.17: Comparison between Version 1 of the Heel Raises exercise (a and b) and Version 2 of the Heel Raises exercise (c and d).

4.8.5 Challenge Added

Even though Free Spirits thrive in creativity and openness, some degree of challenge and goals is needed to keep the novelty of the game. Depending on the kind of challenge, these will also appeal directly to Free Spirits, such as unlockable content and tasks that require exploration. Also, by adding a challenge it is possible to retain more types of players. As defined by Marczewski [92], most players will get into a gamified system for the rewards, and then stay in it for the other features that appeal to them more specifically.

The challenge that was added consists of reaching a new mini-island that is located near the main island where the player starts (The updated map of the game is shown in Figure 4.18). To reach this new location, the user must build a bridge between the two spaces, by purchasing parts to build it with their resources (Figure 4.19). In the new island, the player will find extra locations to do one more set of each exercise (Figure 4.20).

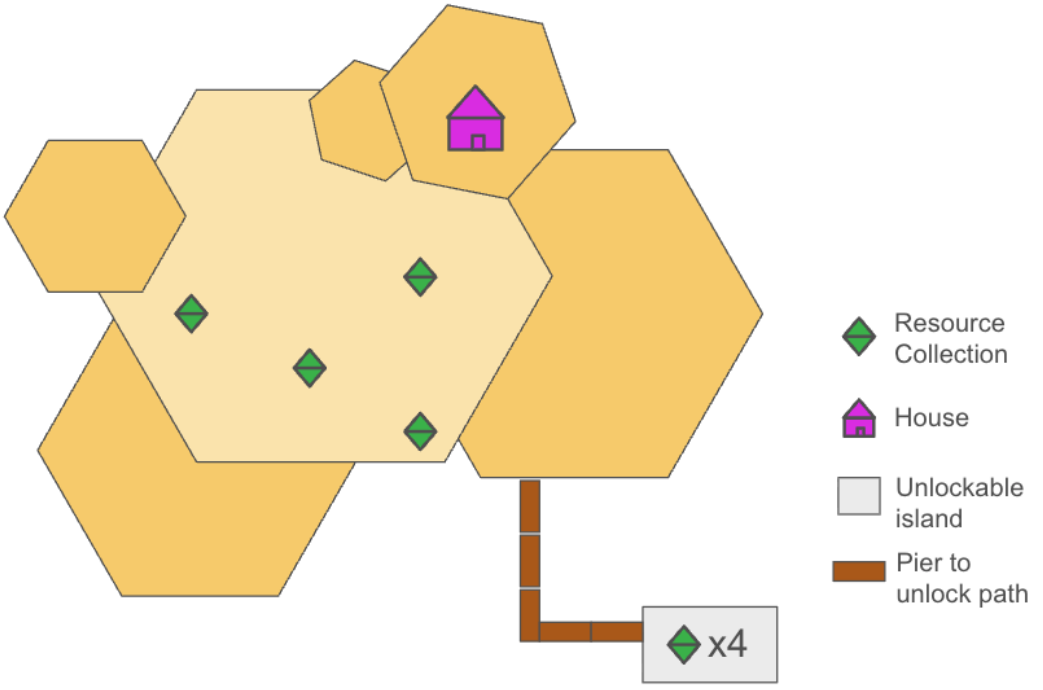
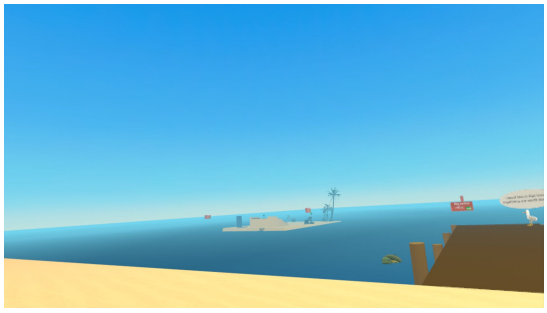
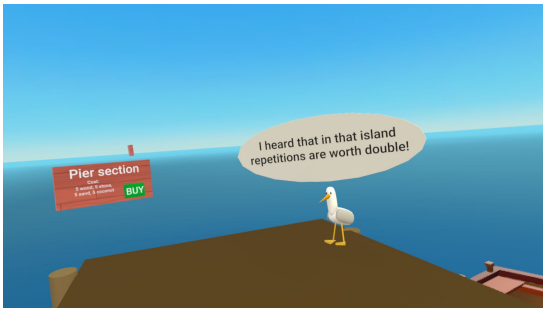


Figure 4.18: Map of virtual environment for the second iteration of the game. Developed in Meta Horizon Worlds.



(a) Unlockable mini-island seen from the main island.



(b) Beginning of the path to unlock the access to the mini-island.

Figure 4.19: Point of view of the player when reaching the beginning of the challenge to unlock the mini-island.



(a) Exercise locations in the mini-island (Lunges and squats).



(b) Exercise locations in the mini-island (Lateral lunges and heel raises).

Figure 4.20: Point of view of the player when reaching the mini-island.

4.8.6 Overview of Participant Feedback

This section describes the adaptations made to the *Cosy ACL* game based on the feedback from the participants during the first user study. These include adding a challenge to the game, an information point, instructions to perform each exercise, feedback on the repetitions made, changes in how to access the exercises (location), and modifications to how the heel raises exercise is presented.

There were some other comments that the participants mentioned from the first prototype that should be considered for future iterations. One comment was the fact that it was a bit difficult at first to do the exercises since the participants cannot see their own feet. An option to fix this issue would be to use Mixed Reality (MR), but this feature was not available in the Meta Horizon Worlds editor at the time of this research, but could be incorporated as an option for the future development of the application. As mentioned by the participants (Section 4.4.3), after a couple of repetitions they gained confidence in their movements, resulting in not needing the visual feedback. This observation highlights the potential of using this gamified application as a proprioception training tool. Patients that have had an ACLR commonly lose some level of proprioception and tend to rely on visual feedback, making their reactions on the playing field slower than before, also increasing their chances of a second injury [168, 167]. In the following chapter, a longer user study is presented, and this feature is discussed with the participants.

Chapter 5

Testing and Results of Cosy ACL V2

To test the second version of *Cosy ACL*, participants were asked to bring the headset home and use it for two weeks. This study was approved by the DCU Research Ethics Committee under reference DCUREC/2023/054. This chapter describes how the second version of the game was tested, and the results obtained from the participants.

5.1 Participants

Participants from the first study (Described in Chapter 4) were contacted by email, describing what the new study is about, the duration, and the tasks to complete. The consent form signed by them for the first study included consent to be contacted after the study about further participation and dissemination of results. From the 5 previous participants who had recovered from an ACL injury, 3 of them agreed to be part of this second study. One of the participants that agreed to participate withdrew from the study before commencing due to an unrelated injury. This resulted in the study having 2 participants.

Participant	Gender	VR literacy	Fitness level	ACL injury	Time since ACLR
8	Female	Medium	Occasionally play sports or attend gym	Yes	7 years
15	Male	Medium	Amateur athlete	Yes	15 years, 4 years

Table 5.1: Information of participants in the study. Medium VR literacy means the participant has used a VR headset once or twice before this study.

5.2 Description of the study

Before starting the study, participants were invited to Dublin City University in order to explain the tasks for the next 14 days, sign a new consent form in agreement with the requirements of the DCU Research Ethics Committee, answer a form about demographic data, and to receive the headset. The results from the HEXAD Gamer Type Questionnaire, and the Feedback Questionnaire Part B were re-used for the two participants in this study, permission to re-use these data was included in the new consent form. After the 14 days had passed, another meeting was set to retrieve the headset from the participants and conduct an unstructured interview about the experience. There were no reminders or contact with participants during the 14-day period of the study to not skew the results related to day-to-day adherence.

The two participants who completed the study were participants 8 and 15 from the first iteration of the game. Table 5.1 shows background information about the two participants.

Participants were asked to play the game once a day over a period of 14 days. The time and place to use the application was chosen by the participants. A period of two weeks for this study was chosen based on the capabilities of the Meta Horizons platform. The platform has a limit of 3D elements, animations, and interactions that can be added to a single game, and these are counted all together. Because of this, the graphical features of the game have to be balanced to provide a better performance. In the case of the CosyACL prototype, enough objects to be purchased by the player were added to allow playability for two weeks without compromising the interactions to do the exercises.

Participants were also given a journal in which they are asked to write the following information after playing the game each day:

- Date and time of play
- What was done in the session (which exercises, purchases of objects)
- Any comments on that particular day

A journal was used to collect the sessions information because the Meta Horizons platform does not save this information on individual playing sessions. With the journal, in addition being able to record in more detail what was done each day, the participant can also record any comment or suggestion they wanted to highlight that day instead of waiting until the end of the study to mention them. This ensured that important comments were not forgotten after 14 days.

An unstructured interview was chosen when meeting the participants after the 2 weeks in order to give them more freedom to express suggestions and comments about their experience with CosyACL. The flexibility of this type of interview allows the participant to talk freely about elements of their experience that were not taken into account when designing the game, given that in that period of time the prototype was used in an unsupervised environment [179]. Comments obtained in this interview can also give context on the activity recorded in the journal, explaining why a participant may have skipped a day of the game or done more exercises than other days.

The unstructured interview at the end of the study was conducted in Dublin City University when meeting the participants to retrieve the headset and the journal. Before starting the interview, participants were reminded of the consent form they signed at the beginning of the study, which included the voice recording of the interview, highlighting that they can withdraw at any time or choose not to be recorded. The recording was done with the Samsung Voice Recorder, and transcriptions were automatically created using the same application. A thematic analysis was done

with the transcriptions of the unstructured interviews, in which the themes were related to adherence to the application during the 14 days, confidence in movements, and features that increased motivation. The quantitative data recorded in the journal (amount of exercises performed, objects purchased in the game, time spent in the game, time of the day) were used to interpret the participants' responses during the unstructured interview as well as their dominant HEXAD gamer type.

5.3 Results

5.3.1 Participant 15

Participant 15 is a 31 year old male who plays sports at least twice a week. His technology literacy is high, although he has only experienced Virtual Reality once or twice. The participant has recovered from two ACL injuries (2010 and 2021). His adherence to rehabilitation was very low for the first injury (2010), and for the second injury (2021) adherence was around 70% of the HEP. The participant reported feeling stiffness on the affected leg a couple of times a week, which he takes as a sign to exercise.

The dominant HEXAD player type of this participant is Player, followed closely by the Free Spirit and Achiever player types (as seen in Table 4.4). Figure 5.1 shows a radar chart of the scores obtained by Participant 15 on the HEXAD User Gamer Types questionnaire, showing that the player types mentioned above are the most dominant ones. It is also clear in this case that this participant is not as interested in features made for Socialiser and Disruptor gamer types. This means that this participant is motivated to play games that include points, rewards, virtual economy, etc but also looks for exploratory tasks, unlockable content, non-linear gameplay, challenges, quests, progression, etc. In the same way, this participant would not be motivated to play games that include social networks, teams, social competition, anarchic gameplay, anonymity, etc (See Table 2.2). This profile of user gamer type aligns with the target audience described for this project.

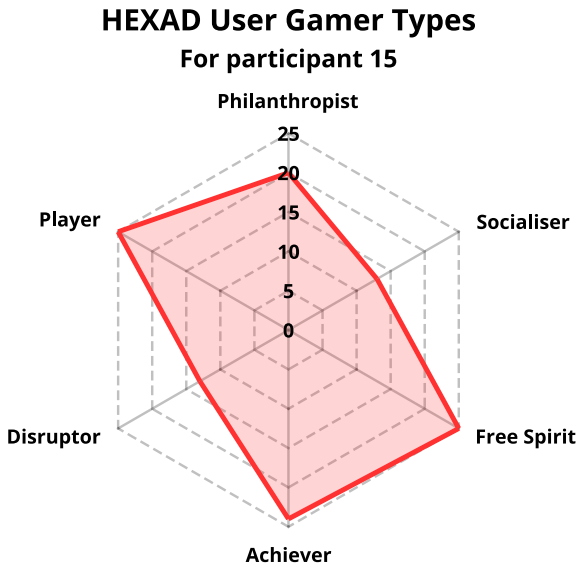


Figure 5.1: HEXAD User Gamer Type for Participant 15.

During the 14 days in which the participant used and played the second iteration of the game, he spent 9.7 minutes on average per session. The participant missed 2 days out of 14, setting his total use of the application to 86%. Table 5.2 shows the time of day that the participant used the application. Looking at the times of day this participant played the game, it is noticeable that the times of day vary drastically during the first 7 days. This participant reported having a hybrid job that allows him to work from home 3 days a week, which is reflected in the times he used to play the game that first week. When asked about the variability of use in the first week, the participant reported that he used the system whenever he had a bit of time and as a way to test if there was a better time of day for him to do the exercises that did not clash too much with his regular day. In the second week, the participant was able to establish a routine in which he played the game early in the morning to fight stiffness after waking up. This variability can also be appreciated in Figure 5.8.

The participant was also asked about the reasons for missing two days, to which he replied that on day 8 he had more commitments than usual and arrived home much later than expected and only realised that he had forgotten the next morning.

On day 12, he went to play a tag rugby match with friends, so he didn't feel like he needed more exercise that day.

Day	Time	Duration
1	19:07 - 19:18	11
2	12:10 - 12:20	10
3	15:25 - 15:35	10
4	20:03 - 20:13	10
5	11:17 - 11:26	9
6	21:16 - 21:25	9
7	07:00 - 07:09	9
8	-	-
9	07:11 - 07:24	13
10	07:12 - 07:23	11
11	07:10 - 07:15	5
12	-	-
13	07:06 - 07:17	11
14	07:04 - 07:12	8

Table 5.2: Times of the day and duration of Participant 15 in the application.

> *"I went to a tag rugby match after work, and by the end of it I didn't think I needed to workout in the game, I got enough exercise and I didn't want to over do it and maybe hurt myself."*

On day 11, the participant had a quick session by doing the exercises once, but knowing this, he did the exercises on the second island, as it gives you more resources for the same work.

> *"There was this one day that I only wanted to do one set of the exercises and realised that I could just do the set of exercises that were worth 20 instead of 10. I felt like I was cheating the system, but I guess it was still a fair thing to do if I unlocked the second island."*

As seen in Figure 5.3, most of the rewards purchases were made in the first week of using the application. The main reason for this, according to the participant, was that a lot of the objects needed more wood, so he needed more days to collect the necessary amount of resources.

> *"I felt like the prices for the rewards were unbalanced, and I did loose a bit of motivation knowing that even though I was collecting the other*

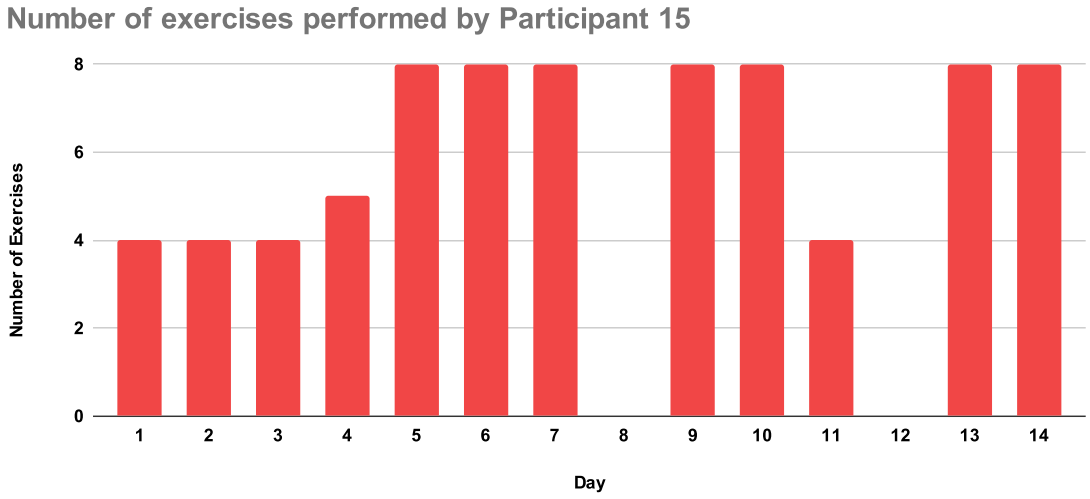


Figure 5.2: Number of exercises performed by Participant 15 each day.



Figure 5.3: Objects purchased in the game each day by Participant 15.

resources, everything needed wood. I had tons of stone, but I could not spend it."

This comment shows that rewards and the ability or difficulty to get them can affect the motivation of the user. It is necessary to carefully evaluate the progression on rewards for this kind of game.

The participant was also asked about their preferences regarding immersion and feedback about their movements, and whether that affected the exercise. The participant used a yoga mat in their workout space as a way to orient himself in the

real-world, which facilitated the adaptation to the virtual world.

> *"The first few days it was a bit awkward to do the exercises, I was afraid of hitting something, but I used a mat to know more or less if I had enough space. On the third or fourth day I got used to it and I was able to do everything faster as I didn't need to accomodate myself."*

He also reported that even though real-time feedback would have been useful, he didn't feel like it was essential, and knowing how the wearable sensors work, he stated that he would not have used them every day because he doesn't want to deal with the setup.

> *"Even if I had the wearable sensors with me, I probably would have used them for only 1 or 2 days and then just skip them altogether, it is an extra hassle, I just want to get into the game and do what I have to do."*

From this participant it was observed that challenges are important to contribute to that feeling of progress, besides being a good motivator to complete the daily workouts. The participant liked that the challenge was about completion rather than a timed task, taking pressure off and giving himself time to think about making the right movements. Complete immersion in the virtual environment did not affect the participant's ability to perform the exercises confidently. Nonetheless, an adaptation period of 3 to 4 days was needed to achieve high confidence in the movements without the need of visual feedback of the lower body. Information from wearable sensors can be useful to provide real-time feedback on the position of the legs if integrated with the system. This participant stated that the wearable sensors are not a long-term solution and it is an added barrier to the daily use of the game as it takes time to set everything up, and sometimes errors to connect or calibrate are present, which is what happened when this participant was part of the first study described in Section 4. This gives space to research easier methods for the user to get their motion data that would not require a complicated setup, or at least a setup that is only done once instead of every time the system is used. An added challenge for

this type of sensor is that there is a bit of a delay between the sensor reading and the update of the positions, so the real-time feedback would not work properly for faster movements.

5.3.2 Participant 8

Participant 8 is a 29 year old female who doesn't exercise regularly since her injury. Her technology literacy is high, but she has only experienced Virtual Reality once or twice. Her injury occurred 7 years ago, during a competition. The participant reported that the adherence to her HEP was low and she was feeling stiff and having some pain on her knee at the moment of starting the study.

The dominant HEXAD player type for this participants is Free Spirit, and the second one is the Achiever player type, closely followed by the Player type (As seen in Table 4.4). This participant is mainly motivated by exploratory tasks, unlockable content, non-linear gameplay, etc, but also enjoys challenges, quests, progression, points, rewards, virtual economy, etc (See Table 2.2). This participant scored the lowest on the Disruptor and Socialiser gamer type, so there is no interest in anarchic gameplay, anonymity, teams, social competition and comparison, etc. This participant also aligns with the target audience for this project. Although she is not an amateur athlete currently, she used to play sports and compete regularly until she got injured.

On average, Participant 8 spent 12.5 minutes in the game per session. The participant did not miss any day during the 14 days of the study, setting her total application use at 100%. Table 5.3 shows the time of day the participant used the application. Unlike Participant 15, Participant 8 easily established a routine for the use of the game. Handling a full-time job that requires her to be in the office in-person made it difficult for her to play the game during the day and reported that the late night workouts using the VR helped her relax after a long day.

This participant showed good adherence in the game throughout the two weeks, performing all exercises and the extra ones almost every day. The first thing she

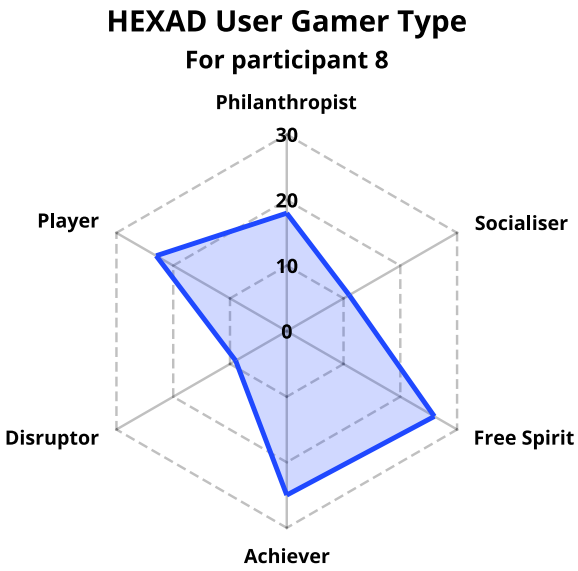


Figure 5.4: HEXAD User Gamer Type for Participant 8.

Day	Time	Duration
1	21:20 - 21:40	20
2	22:50 - 23:05	15
3	23:00 - 23:20	20
4	23:00 - 23:20	20
5	22:00 - 22:10	10
6	22:50 - 23:00	10
7	23:15 - 23:30	9
8	23:10 - 23:22	12
9	23:15 - 23:25	10
10	23:00 - 23:10	10
11	23:00 - 23:10	10
12	23:05 - 23:12	7
13	23:10 - 23:17	7
14	20:30 - 20:40	10

Table 5.3: Times of the day and duration of Participant 8 in the application. Average time: 11.23 minutes. Median time: 10 minutes.

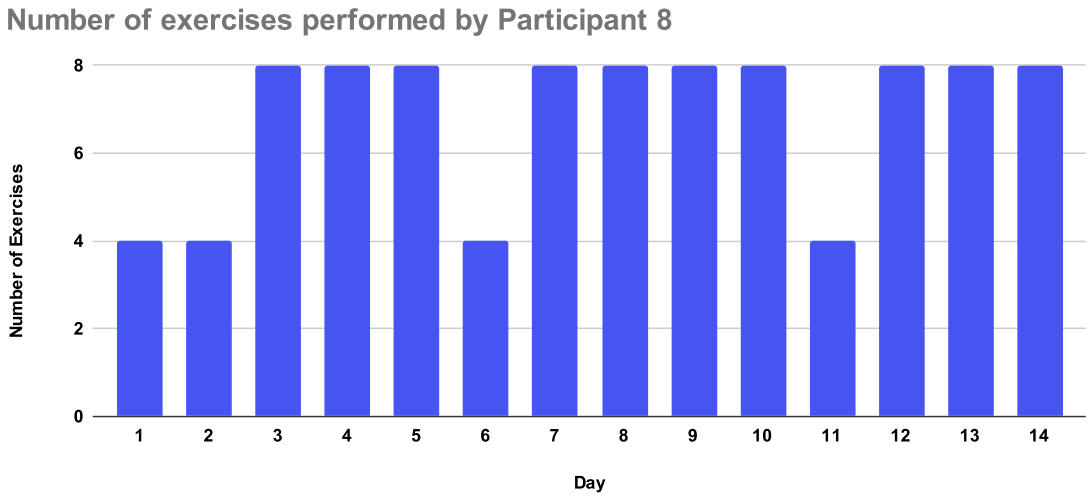


Figure 5.5: Number of exercises performed by Participant 8 each day.

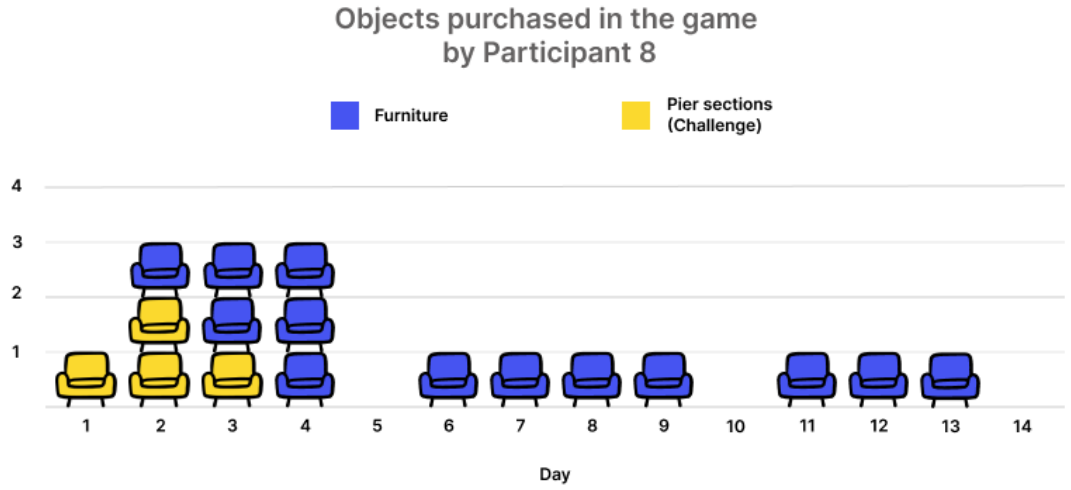


Figure 5.6: Objects purchased in the game each day by Participant 8.

did in the game was the challenge of unlocking the second island. As seen in Figure 5.6, Participant 8 purchased all sections of the bridge during the first 3 days. She reported feeling motivated by the expectation of exploring another part of the virtual world.

> *"I wanted to explore all of the island, and when I saw that I could build the bridge to another island, I got excited to see it. I was a bit impatient for it too, I wish there was more of this kind of challenge."*

There were only 3 days in which the participant did not purchase any reward, for days 5 and 10, the main reason was that some objects needed more resources and she needed an extra day to "save" for the reward. In the case of day 14, she did not purchase a reward because there were none left in the prototype to get.

> *"On the last day, after doing the exercises, I kept looking for more things to get, but it seemed like there were no more objects. I felt kind of sad for that, but at the same time I felt like I won the game."*

Also, as seen in Figure 5.5, she did the basic and extra exercises each day, except for days 6 and 11, to which the participant reported being too tired from work, but wanting to get at least the basic exercises in. Curiously, on the days she only did one set of exercises, she did the original ones, not the ones that were worth more. This behaviour matches her results of the HEXAD questionnaire, in which she scored very low on the Disruptor gamer type, so it is unlikely that she would be looking for a way to "cheat the system".

During the unstructured interview, the participant was asked about her experience using the game and not being able to see her legs while doing the exercises. The participant stated that on the first few days she was slower when performing the exercises to make sure everything was done correctly, but on the 4th day or so she was feeling confident on her movements. After this answer, the participant was asked about her thoughts on making a mixed reality version of this game, where she would be able to see her legs. The participant reacted with a big negative for this

option, saying that the complete immersion on the virtual world was very good for her because she used it at night and that she thinks that doing mixed reality would break the illusion of being in the island.

> *"On my journal you can see that I always played very late at night, and it really helped that it was daytime on the game, and the sound of the waves was very relaxing and I felt great afterwards and went to sleep very happy with myself."*

> *"I don't think mixed reality would have improved the game, for me it would have ruined it, the daylight on the game would have looked weird against the night of the real world and I would not have felt immersed."*

Participant 8 was also asked about the use of wearable sensors to obtain real-time feedback, to which she responded saying that it may be useful, but the setup still seems to take more time, especially if it needs to be calibrated each time.

> *"I didn't feel like I needed the feedback, but maybe the doctors would like it. In my case I don't think I would use them, it seems that it would take too much time and it would put me off playing."*

Also, she mentioned that she was able to relax and play very late at night because she was not making noise that could disturb the other people that live with her. This is because the sound on the headset can only be heard by the participant. When asked about how she felt by the end of the two weeks, Participant 8 reported feeling a lot less stiff and more motivated to do sets of exercises everyday, as it was a fun activity that didn't take too much time and that she could do at home. Convenience and motivation was a big part of the successful adherence on the game.

> *"I definitely would not have done any exercise during these 2 weeks if it weren't for the game."*

> *"I also feel that my knee is stronger compared to two weeks ago"*

From this participant it was learned that exploration plays a big role on motivation, and designing challenges that contribute to this are essential for a Free Spirit player. It is important to note that this participant went from doing no exercises at all to incorporate at least 4 sets of exercises each day, showing the potential of cosy game features in motivation for physical activity. She was very engaged and wanted to log in every day to improve her virtual space and continue exploring the island even though her only available time was very late at night (See Table 5.3). As with Participant 15, Participant 8 felt the inclusion of the wearable sensors could be an added barrier. This participant also reached a good level of confidence in her movements around day 4. The results from this study show the effectiveness of cosy characteristics to motivate physical activity in players whose main player type is Free Spirit.

5.3.3 General Results

Even though the two participants have differences in their routine, lifestyle, etc, some observations can be made when looking into their results together.

Figure 5.7 shows the time spent in the game for each participant, plus the average time and the median time. It is clear that Participant 8 spent more time in the application than Participant 15, but both of them spent more time in the VR during the first few days, compared to the last few days of the study. In both cases, the participants reported that after a few days they were more familiar with the environment, which made them go and look for the exercises right away. This familiarity also applies to the performance of the exercises, in which both participants commented feeling more confident in their movements around day 3 or 4 and, thus being able to finish their workouts faster.

Figure 5.9 shows the combined gamer type radar chart of the two participants that tested the application for 2 weeks. There are similar tendencies in the type of gamer of the two participants, but the main difference that is visible is that Participant 8 has an even lower interest in game features for Disruptors and Socialisers than

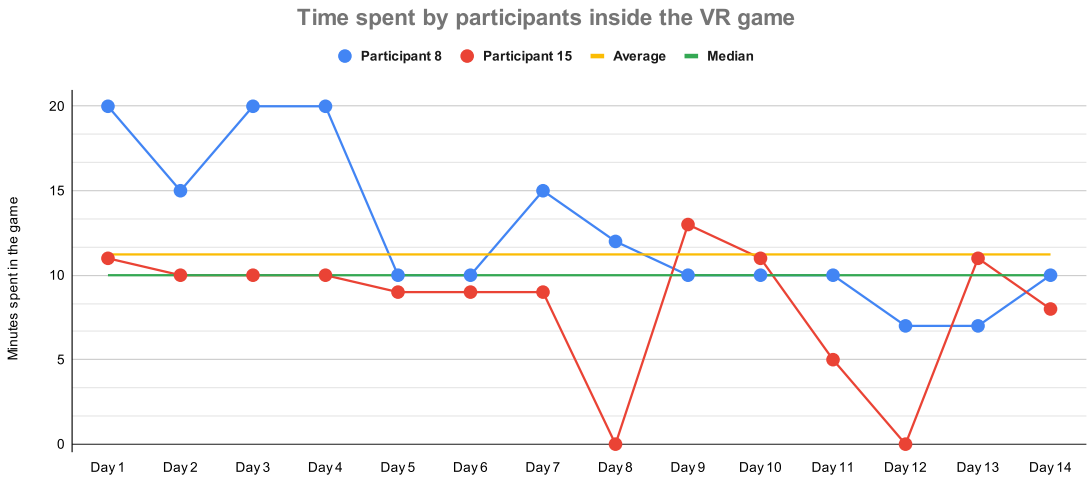


Figure 5.7: Time that each participant spent inside the game during 14 days.

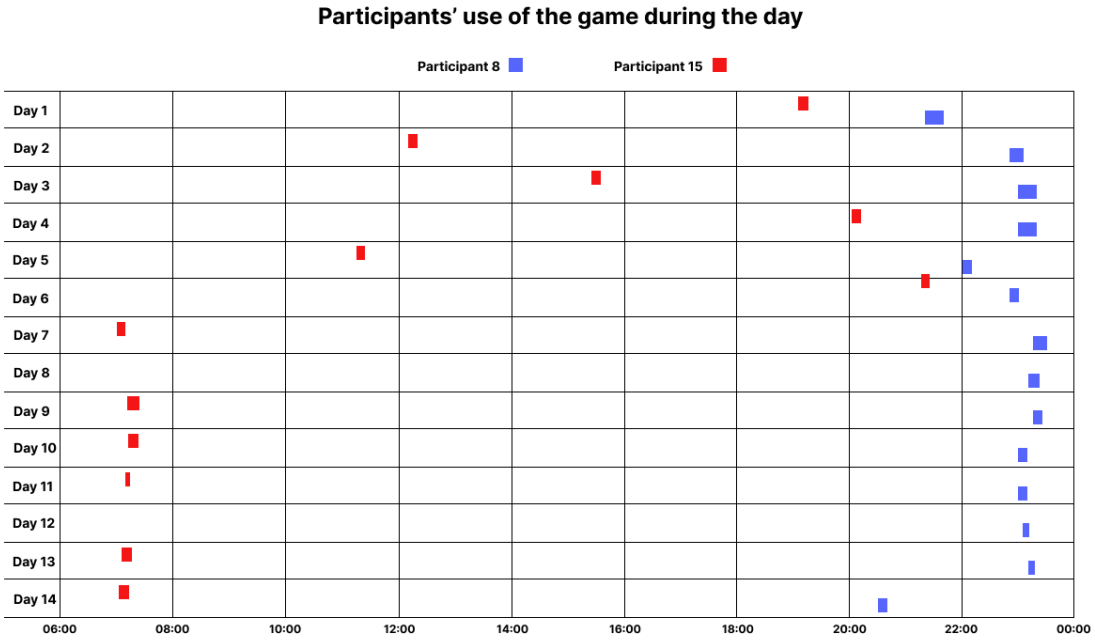


Figure 5.8: Participants' use of the game during the day.

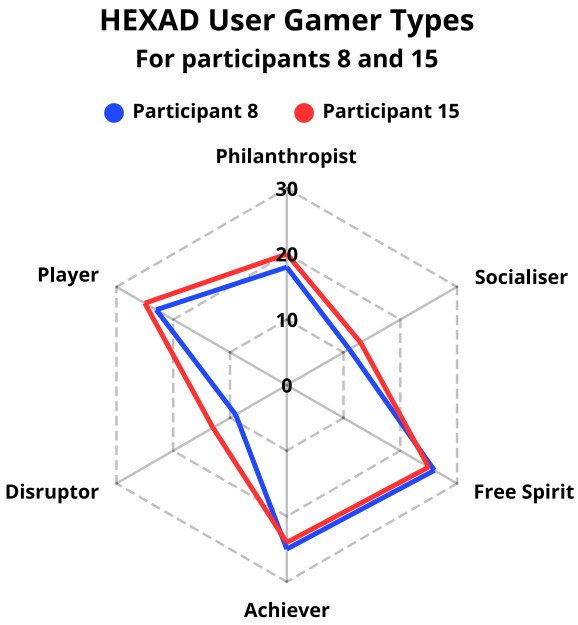


Figure 5.9: HEXAD User gamer Type for Participants 8 and 15.

Participant 15. Participant 8 showed a higher interest for exploratory tasks than Participant 15, and highlighted her enjoyment towards the virtual environment and being able to go around and relax no matter the time of day. Even though Participant 15 also enjoys the exploratory tasks, his motivation lowered after completing the challenge, showing that if more of these challenges are added, his adherence to the game can improve.

RQ2 is being addressed in the two user studies as some features provided by VR, such as immersion and portability, help to increase adherence in the exercises. These features directly handle some of the barriers described in Section 2.3 (External factors, No relation with sport). For the "External factors barrier", the main issue is transportation to a clinic, but as this system is designed for home use, eliminates the need to travel somewhere else and therefore allowing the patients to be more independent during their rehabilitation. The immersion offered by the VR helps with the barrier that we have called "No relation with sport", as the main complaint of patients had to do with the usefulness of the exercises in their activities or sport. The gamification scenario that was designed creates the need for the exercises to be executed to make advancements in the game. This way patients get the feeling that the exercises are helpful for their own goals.

The results of this study also answer RQ3 by showing that there is potential in using cosy gamification features in rehabilitation games to tailor them to users with specific gamer types like Free Spirits, increasing motivation and adherence in the exercises. The use of cosy game elements tackles the remaining barriers that ACL patients face: Kinesiophobia, Feelings of isolation/Boredom, Expectations management. The game is made to be self-paced and relaxing so the patients don't have to rush into doing their exercises which they are already nervous about, helping to overcome kinesiophobia. The game still encourages the players to explore and find elements to advance in the game, without the use of competition or leaderboards, keeping the game entertaining without adding pressure to the patient, reducing the feeling of boredom. Finally, gamification provides a visual aspect that helps the user see their own progress. If more exercises are done, the player will have more resources in their inventory, and hence be able to improve their virtual environment. Small progress is still visible in the game, showing the patients that the work done is still noticeable, reducing the feeling of being stuck in the rehabilitation process.

Chapter 6

Conclusion

This thesis explored the use of cosy game features in a VR rehabilitation exergame with the goal of helping patients overcome the most common barriers that prevent them from completing their HEP. *Cosy ACL* was designed as a relaxing exploration game, addressing a gap in the field of rehabilitation exergames that currently focuses on competitive themes. This work demonstrates the efficacy of a low-stress gaming environment to support recovery from injuries that bring stress due to athletes being unable to return to their sport. *Cosy ACL* provides an immersive environment to escape to and allows the player to collect resources by performing rehabilitative exercises and subsequently spend their rewards to make improvements to their virtual space. Pilot testing was completed, involving an iterative user-centred design process. The first prototype was tested on 15 participants in a laboratory setting, and following the feedback obtained, a second prototype was tested in the home environment with two participants over a period of two weeks. The results of this work show positive feedback from users in the use of the game to comply with prescribed exercises and thus opens a research path on exergames using a slow-paced gameplay, such as cosy gaming, to obtain a higher adherence rate and compliance with HEPs for rehabilitation.

In this concluding chapter, the design implications and contributions of this work will be discussed, followed by a summary of how the research questions have been addressed. From this work, a list of design recommendations is presented

for the development of future exergaming systems for home rehabilitation. Finally, limitations and future directions of this work are discussed.

6.1 Design Implications and Contribution

Recovering from an injury such as an ACL tear can be a slow and painful process in which obstacles and barriers are found each step of the way. To create an experience that helps combat the feelings of defeat that a patient may experience and improve adherence to physical therapy, it is imperative to observe what is stopping the patients from progressing and to identify what motivates them.

In Chapter 2, the main pain points of patients with ACL injuries were outlined, classifying them into five main themes (See Figure 6.1): Kinesiophobia, feelings of isolation/boredom, no relation with sport, expectations management, and external factors. Gamification is often the path chosen to distract the patients and introduce enjoyment in rehabilitation, but different game elements can motivate or discourage different people, as described in the HEXAD User Gamer Type Framework (Section 2.4.1). This framework identifies six types of player (Achiever, Philanthropist, Free Spirit, Player, Socialiser, and Disruptor) with their corresponding game elements. This information, combined with research on current trends of gamification (Section 2.4.2), uncovered a gap for gamified rehabilitation. Most of the research done on gamification for physical rehabilitation only includes game elements such as points and levels, followed by challenges and leaderboards, appealing only to users identified as Players and Achievers. This contradicts the tendency of game elements which motivate users in the long term, given that the most common gamer types are Philanthropists, Free Spirits, and Achievers. This project focused on designing a gamified rehabilitation application tailored to Free Spirits.

The design takes into account the barriers that an ACL patient faces and includes game elements to appeal to Free Spirit players. The combination of cosy gaming elements and VR offers a solution to the fears and obstacles of a patient with a knee injury. This research highlights the importance of designing for the users based on

their pain points and elements that motivate them to use the system.

The main contribution of this research is the design of a gamified rehabilitation virtual reality application based on the barriers that patients face and the game elements preferred by Free Spirit gamer types. The results after testing on participants are promising for improving adherence on the prescribed HEP in the long-term. Although the longest test lasted two weeks, the participants involved reported good levels of motivation throughout that time and claimed that they would have kept playing for a longer time. The use of cosy gaming features also shows that this relatively new genre of games can be used to design rehabilitation and health applications.

6.2 Research Questions

RQ1: Which motion-sensing technology provides the best capabilities to measure parameters that are important for managing the rehabilitation process at home with a VR system?

This question is addressed in detail in Chapter 3, where different commercially available sensors were discussed: three types of IMU-based sensors and one bend sensor. The IMU sensors work in similar ways, they are composed of small sensors that are positioned on the body where each sensor detects the position of the joint where it is located. This setup gives important information to physicians as the movement of the patient can be observed. The minimal setup would require five sensors to track the lower body - one sensor in each ankle, one sensor in each knee, and one sensor in the hip. The sensors that were explored have different usability issues, mainly from the calibration process, which requires technical knowledge and calibration each time they are used, and sometimes a second calibration is needed if the signal gets lost during the movements. The Mocopi sensors were the most promising set of sensors, as their software is free to use and it records in BVH files. Even though there were more advantages on these sensors, the usability issue related to calibration also exists, and sometimes the sensors would take a long time

to connect and get the readings. This generated impatience in the participants of the first study (Section 4.5), finally deciding to carry out the study without taking readings from them in most cases.

A bend sensor was also explored, with an easy and quick calibration process, but this sensor alone would not give physicians enough information to know how patients perform the movements, it would only be possible to know the Range of Motion of the knee. Although this is important information for recovery, it is not enough to get a full picture of the patient's state.

It was concluded that the sensors mentioned above could collect motion data that is useful to physicians, as long as they are used under the supervision of a person with technical knowledge of their use. Unfortunately, IMU sensors are still not feasible for unsupervised use in the home by players. Calibration is needed each time they are used and, without the proper setup, the data captured may be completely inaccurate. Participants who used our system for a longer period of time also stated that they would not use these sensors as it would represent an added barrier to them.

In Section 4.5, a comparison between the use of a VR headset and not using it while doing the forward lunges exercise is shown. The participant was recorded on video and then analysed using the Kinovea software to measure angles. This analysis shows that there is no significant difference in the performance of the exercise while wearing the VR headset compared to not using it. This suggests that the users, although they are not able to see the position of their legs, will still perform the exercise correctly after some practice, helping them train their proprioception as well.

The limitation of not having real-time feedback of lower limb positions in the VR application still exists, but more research needs to be done in order to include wearable sensors that can truly be used by the patients with no supervision.

RQ2 Does Virtual Reality have the potential to enhance adherence in people recovering from knee injuries?

Virtual Reality, as described in section 2.8.1, helps immersing the user in a virtual environment to offer some distraction. For *Cosy ACL*, an island was chosen as the virtual scenario. Besides the space itself, ambient sounds were added, resembling waves and sea birds. Participants who tested the application reported feeling more relaxed due to these features that VR provides. One of the participants who tested the application at home highlighted that it helped her relax and motivate herself to do the exercises, as she would use it very late at night. This work shows that a relaxing virtual environment can also help patients increase their adherence in the HEP.

At the moment, a VR headset cannot track the position of the lower body by itself, so users can't see their legs while using it. However, this may also help in training proprioception, which ACL patients partially lose after the injury [167]. In this project, participants reported having some doubts and difficulty at first when performing exercises, but after a couple of days they got used to it and had no issues completing the repetitions. Proprioception training decreases the incidence of another ACL injury by requiring players to perform activities and exercises without visual feedback [180]. Fully immersive environments like the one offered in the designed application offer a safe space to regain proprioception.

As shown in Figure 6.1, VR provides portability to the users, which would help with the external factors barrier. The portability allows patients to do their workouts at home at the time that is more convenient for them. For instance, Participant 8 only had time for the exercises very late at night, a time of the day in which no clinic or gym is open or available. It also eliminates commuting times to other places to work out, helping patients to have more time to organise their days and not rely on others for transportation.

Another barrier identified was the feeling of losing motivation when they saw no application of the exercises in their particular sport, but this extends to the feeling of doing movements with no apparent usefulness. VR offers immersive environments that allows personalisation of the experience. In this application, the exercises

to perform were designed for the player to do an activity that blends with the environment they are in even though it is not modeled as playing a specific sport. For example, heel raises are designed so that the player can reach out for coconuts on palm trees. Future versions of the game can include some forms of sport, depending on the exercise that is to be included.

In summary, VR offers portability to allow home-based rehabilitation, and immersion to motivate patients with different strategies and environments. The use of VR can also be helpful in training proprioception in ACL patients, taking into account that this work found no significant difference between doing forward lunges using a VR headset and doing them without any other equipment.

RQ3 Does a cosy game dynamic have the potential to enhance exercise adherence in people recovering from knee injuries that have been identified as Free Spirits?

Current literature mostly uses game elements such as points, levels, and scoreboards to motivate a patient during rehabilitation. These game elements attract users identified with the Player and Achiever gamer types, not taking into account the other four gamer types (Free Spirit, Philanthropist, Socialiser, Disruptor). The literature review for this work (Section 2) demonstrated that there is a gap in the research for rehabilitation exergames that are suitable for players identified as Free Spirits, which represent nearly 20% of users. This work involved the creation of a user-centered design of a rehabilitation exergame that uses cosy game features to appeal to other types of players that have not been considered in the past. This application was tested with real ACL patients that aligned with the Free Spirit gamer type and achieved positive results in adherence during a period of two weeks. The participants highlighted that they were more motivated to exercise and felt less anxious about performing some exercises thanks to the slow-paced dynamic of the game.

Game elements that appeal to Free Spirits, such as exploration tasks, unlockable content, and non-linear gameplay are also features commonly found in cosy games,



Figure 6.1: Barriers identified for patients with ACL injuries and the features from VR and Cosy gaming that provide a solution to those barriers.

aiding in the improvement of the feelings of boredom and isolation that ACL patients experience during their recovery. Unlocking content in the island also serves as visual progress tracking in the game. After testing the game, the involved participants reported enjoyed exploring the island, looking for new things to discover and performing the exercises in order to unlock objects and spaces such as the second island.

The main barrier patients face during their rehabilitation process is kinesiophobia, fear of movement, of the possibility of causing more pain by moving the wrong way. Cosy gaming offers feelings of safety and a low-stress environment, as explained in Section 2.5. Participants who tested the application highlighted that the environment was relaxing and that there was no pressure to complete tasks quickly, which helped them focus when performing each repetition.

It is important to note that this solution will not fit everybody, it will depend on the gamification preferences of the users. This application was designed to provide motivation to patients identified as Free Spirits in the HEXAD Gamer user type framework, as there has been little to no research in exergames for rehabilitation specific to this type of gamer.

The conclusion to this research question is that cosy games have features that motivate users to keep playing, especially when the players are identified as Free Spirits. The slow-paced gameplay and possibilities of exploration are some of these features, but these characteristics also match the needs of ACL patients when recovering from surgery. Cosy games take the pressure off instead of adding it, most games for rehabilitation focus on points and leaderboards, making recovery more of a competition. In this work, cosy gaming elements is shown to have the potential to help with barriers identified in Chapter **??**, namely Kinesiophobia, Feelings of isolation/boredom, and Expectations management.

6.3 Design Recommendations

As a result of this work, this section summarises its findings as a list design recommendations for a VR rehabilitation exergame that aims to increase adherence in Free Spirit gamer types.

- **Open world that allows for exploration:** Free Spirits, as their name says, value freedom in their way of playing. Having a large virtual environment with room to explore and discover is essential for them. *Cosy ACL* takes place on a deserted island where players can walk around and explore every corner of it.

- **Challenges to unlock new spaces:** The exploration along with tasks and challenges to unlock spaces or objects, motivates Free Spirits as well as Achievers to advance in the game. It is also important that these tasks are not linear in order not to disturb the freedom that these players value so much. In *Cosy ACL*, as a complement to the open world, there is a challenge where the player needs to build a bridge to get to a new space of the island.

- **Non-linearity:** Part of the freedom granted to Free Spirits also means not forcing the tasks upon players to be done in a certain order. *Cosy ACL* allows the players to perform their exercises in the order they prefer.

- **Exercises should match what is being done in VR:** One of the barriers that was mentioned in Chapter 2.3 is that patients fail to see the usefulness of exercises within their sport. The exercises included in *Cosy ACL* matched activities that should be done to collect resources on the island. Although the game is not happening on a sports field, by matching the movements with the activity, players can do the exercise in a seamless way, making it feel like completing game tasks instead of completing repetitions.

- **Personalisation options:** Free Spirits enjoy expressing themselves, so allowing the player to personalise their environment motivates them to come back.

In this game, the player could "purchase" furniture to decorate their house and space. A future version should include the ability to change the colours and positions of objects.

- **Slow-pace (no races, timed activities, or competitions):** This applies not only to Free Spirits, but to ACL patients that might be anxious about exercising, which was the most common barrier identified. By taking out the rush on the game, the player can focus on completing the repetition correctly instead of trying to do things fast. In *Cosy ACL*, the focus is on completing the number of repetitions required, but time is not counted, and the speed is not mentioned or saved.

- **Progress tracking within the game:** ACL patients also present problems in expectations management, in which they want a quick recovery and fail to feel progress in a short amount of time. It is important to find a visual strategy to show the patients that they have done enough work on their recovery. In *Cosy ACL*, there is feedback within each mini-game by informing how many repetitions have been made. Also, the player can visualise progress by looking at their resource inventory and even how much their virtual environment has changed due to their own personalisation of the space. There is a clear contrast in seeing a bare deserted island compared to a well-equipped and personal house.

6.4 Limitations and Future Directions

The main limitation of this work, and current implementations to date, is not having accurate monitoring of the lower limb positions in real-time while in the game. The best method approach that was found for this project was using recorded video. This method could be used to monitor a patient's movement during unsupervised exercise at home by the patient recording themselves and providing the physician with the videos for later analysis using software like Kinovea. This option requires

less technical knowledge from the patients than using the wearable sensors, but creates other issues like the patient setting up the recording correctly, storage limitations in the patient's recording device, and remembering to send the video to their physician.

Using the VR headset itself, there are some ways of broadly detecting the execution of some of the exercises, such as using the height and position of the headset to tell if a person is lunging down or lunging to the side. However, there is a limitation in the accuracy of the position which would not provide physicians with detailed information. With the existing approach, physicians would be able to know if the patients did their exercises by observing their progress in the game. The cost of a VR headset is also a limitation in terms of access to the system in a healthcare environment. Different VR headsets range from €250 to €1000+, which makes the technology expensive and possibly inaccessible for low-income individuals to acquire on their own. The participants that took part on the second study were young, highly educated individuals, living in a high-income country. The particular conditions of these participants make them more likely to have experienced VR technology before, and more likely for them to continue using this technology on their own resources. For healthcare centres and physiotherapy clinics, the investment in this equipment may help improve waiting times for patients, and better adherence to the HEP can result in better outcomes for the patients. This application also requires patients to have a higher technology literacy, as Virtual Reality is still not commonly widespread as other technologies, such as mobile phones.

By not having the real-time position of the patient's joints, cheating in the game is possible, as the current version of the game only requires the user to grab an object from the floor. During the testing of the application, participants did not try to take advantage of that, but it is still a strong possibility. Instead, multiple participants tried to do more sets of exercises to collect more resources, but this was not allowed in the game to avoid over-exercising. Another limitation that affects any VR application is the availability of physical space for the user. If the user does

not have enough space to freely do the exercises, then it cannot be used effectively. Future testing would require more participants and a longer period of time.

Four exercises were tested to demonstrate the feasibility of the system. For more thorough testing of its rehabilitation potential, more exercises need to be added, as well as expanding the game in terms of rewards and unlockable content. A bigger portfolio and a way to select sets of different exercises every day can provide a feeling of variety to patients. Also, physicians would be able to select exercises that are more suitable for the patient at each stage of recovery.

Another limitation for this research is the small sample of participants that took part in the studies due to a difficult recruitment process. A larger study is needed to have a wider variety of backgrounds that can provide different forms of feedback to improve the application.

This work opens up a research path around the design of gamified rehabilitation experiences based on the type of player the patient identifies with. In this work the application was centered on Free Spirits, but a future version could also include elements appealing to Philanthropists (Described in Section 2.4.5), as they are also one of the most common gamer types. This can be done by adding collectibles earned by completing certain tasks, and allowing trading too. Exploring the use of administrative roles and knowledge sharing can also make the game a great experience for more types of players. The gameplay of this game has the potential to add more gamification elements that can appeal to a broader range of players.

This research shows that a rehabilitation exergame does not have to be competitive to be appealing to the users, that it can also be a relaxing and enjoyable experience while patients take their time to recover from their injuries. It is also important to provide patients with a suitable gaming experience based on their gamer types, because in the real world for this application there is no single solution where "one-size-fits-all".

Appendix A

Research Outputs

The research outputs during my PhD are divided into three categories: Publications, which will show publications directly related to my project; Project Collaboration, shows publications in which I collaborated; and Science Communication and Events, where I mention events where I presented my work.

A.1 Publications

- Colorado, L. A. M., Baberwal, S. S., Gunawardhana, K. S. D., Moran, K., & Coyle, S. (2025, October). Understanding Barriers in Physical Engagement: Prototyping an Exergame for Anterior Cruciate Ligament Rehabilitation. In 2025 IEEE International Workshop on Sport, Technology and Research (STAR) (pp. 162-167). IEEE.

  Abstract Anterior Cruciate Ligament (ACL) tears are severe and relatively common injuries with potential long-term consequences. Rehabilitation is a vital part of recovery, but patients frequently have trouble adhering to their Home Rehabilitation Programme (HEP) long-term. There are several reasons for this, (e.g. pain, boredom, having no expectations, etc). This paper aims to present a first step towards a Virtual Reality (VR) application that can improve adherence to the HEP. An analysis of themes is undertaken to identify why patients have difficulties in continuing their HEP, and based on

this, a storyboard for a VR application is created with the forward lunges exercise as a case study. After the storyboard, a mid-fidelity prototype is designed and tested by one participant to obtain feedback and improve the prototype in a future second iteration. The participant's responses show potential for improvements of the prototype in terms of presenting the game and the environment for a better experience. The use of Meta Horizon Worlds as a prototyping tool allows for faster iteration without the complications of developing a high-fidelity VR application. The importance of discussing barriers with patients, storyboarding and prototyping is highlighted and discussed, showing that they are important steps to create a VR application that will be used to improve a monotonous exercise.

- Magre, L. A. (2024, October). Designing for Engagement: Cozy Gaming for Long Term Goals. In Companion Proceedings of the 2024 Annual Symposium on Computer-Human Interaction in Play (pp. 431-433).

  Abstract Long-term adherence to a Home Exercise Programme (HEP) is a difficult task for many athletes after an Anterior Cruciate Ligament Reconstruction (ACLR), making it difficult to go back to play sports. There are some common barriers that contribute to the tendency of patients not continuing with their HEP, like fear of re-injury, boredom, and lack of expectations. In my PhD research, I am using a user-centered approach to determine design guidelines for an immersive VR application for physical therapy, focused on ACL injuries. After identifying the needs of the users, cozy gaming characteristics have been chosen in order to design this application. Initial literature review and feedback has shown that a relaxing and task-oriented game could increase engagement on the prescribed exercises.

- Magre, L. A., & Coyle, S. Smart Garments for Immersive Home Rehabilitation Using VR [DC]. 25th ACM International Conference on Multimodal Interaction (ICMI 2023). 9-13 October 2023, Paris, France.

Abstract Adherence to a rehabilitation programme is vital to recover from injury, failing to do so can keep a promising athlete off the field permanently. Although the importance to follow their home exercise programme (HEP) is broadly explained to patients by their physicians, few of them actually complete it correctly. In my PhD research, I focus on factors that could help increase engagement in home exercise programmes for patients recovering from knee injuries using VR and wearable sensors. This will be done through the gamification of the rehabilitation process, designing the system with a user-centered design approach to test different interactions that could affect the engagement of the users.

- Magre, L. A., & Coyle, S. Poster & rapid fire abstracts. User-centred design of a VR based rehabilitation system- A preliminary study to overcome the barriers of rehabilitation from Anterior Cruciate Ligament Reconstruction. 16th Irish Human Computer Interaction Symposium (iHCI 2023). November 17 2023, Dundalk Institute of Technology, Dundalk, Ireland.

A.2 Project Collaboration

- Gunawardhana, K. S. D., Fang, Z., McGuinness, G. B., Colorado, L. A. M., Baberwal, S. S., Wani, W. A., ... & Coyle, S. M. (2025). Innovative Self-Powered Sensing: Potential of Fabrigami and Electrospun Nanofiber-Based Triboelectric Nanogenerator for Joint Biomechanics Monitoring. Small, e06363.

  Abstract This work presents a high-performance, self-powered triboelectric nanogenerator (TENG) embedded into an origami-inspired fabric ("fabrigami") structure for real-time joint biomechanics monitoring. The device consists of electrospun polyvinylidene fluoride (PVDF) as the electronegative layer and silver-doped cellulose acetate (Ag-CA) as the electropositive layer, with enhanced surface charge density and mechanical durability. The fabrigami ar-

chitecture amplifies contactseparation dynamics, enabling efficient detection of movements during joint motion while preserving conformability and air permeability. The optimized TENG based on 1.5% Ag in CA against PVDF exhibits remarkable electrical output characteristics, including an open-circuit voltage of 155.9 V, short-circuit current density of 8.134 mA m-2, and transferred charge density of 65.62 muC m-, with an instantaneous peak power density of 0.029 W m-2 achieved through an 11 MΩ external load resistance. The power conversion efficiency is 4.6-92.8% for 100-5 μm elastic compression of electrospun samples under 10 N, 2 Hz actuation. Sensor stability is observed over 15 000 cycles. The fabrigami knee sleeve includes a Bluetooth-enabled microcontroller transmitting real-time motion data wirelessly to measure joint angles and distinguish movement activities. This work demonstrates a novel strategy combining material innovation (Ag-CA nanofibers) with structural configurability to create a breathable and power-autonomous smart textile.

- Baberwal, S. S., Magre, L. A., Gunawardhana, K. S. D., Parkinson, M., Ward, T., & Coyle, S. (2024). Motor imagery with cues in virtual reality, audio and screen. Journal of Neural Engineering, 21(5), 056020.

  Abstract Objective. Training plays a significant role in motor imagery (MI), particularly in applications such as Motor Imagery-based Brain–Computer Interface (MIBCI) systems and rehabilitation systems. Previous studies have investigated the intricate relationship between cues and MI signals. However, the medium of presentation still remains an emerging area to be explored, as possible factors to enhance Motor Imagery signals. Approach. We hypothesize that the medium used for cue presentation can significantly influence both performance and training outcomes in MI tasks. To test this hypothesis, we designed and executed an experiment implementing no-feedback MI. Our investigation focused on three distinct cue presentation mediums—audio, screen, and virtual reality(VR) headsets—all of which have potential implications for BCI use in the Activities of Daily Lives. Main results. The

results of our study uncovered notable variations in MI signals depending on the medium of cue presentation, where the analysis is based on 3 EEG channels. To substantiate our findings, we employed a comprehensive approach, utilizing various evaluation metrics including Event-Related Synchronization(ERS)/Desynchronization(ERD), Feature Extraction (using Recursive Feature Elimination (RFE)), Machine Learning methodologies (using Ensemble Learning), and participant Questionnaires. All the approaches signify that Motor Imagery signals are enhanced when presented in VR, followed by audio, and lastly screen. Applying a Machine Learning approach across all subjects, the mean cross-validation accuracy (Mean±Std. Error) was 69.24±3.12, 68.69±3.3 and 66.1±2.59 when for the VR, audio-based, and screen-based instructions respectively. Significance. This multi-faceted exploration provides evidence to inform MI-based BCI design and advocates the incorporation of different mediums into the design of MIBCI systems, experimental setups, and user studies. The influence of the medium used for cue presentation may be applied to develop more effective and inclusive MI applications in the realm of human–computer interaction and rehabilitation.

- Dinuwan Gunawardhana, K. S., Simorangkir, R. B., McGuinness, G. B., Rasel, M. S., Magre Colorado, L. A., Baberwal, S. S., ... & Coyle, S. M. (2024). The potential of electrospinning to enable the realization of energy-autonomous wearable sensing systems. ACS nano, 18(4), 2649-2684.

  Abstract The market for wearable electronic devices is experiencing significant growth and increasing potential for the future. Researchers worldwide are actively working to improve these devices, particularly in developing wearable electronics with balanced functionality and wearability for commercialization. Electrospinning, a technology that creates nano/microfiber-based membranes with high surface area, porosity, and favorable mechanical properties for human in vitro and in vivo applications using a broad range of materials, is proving to be a promising approach. Wearable electronic devices can use me-

chanical, thermal, evaporative and solar energy harvesting technologies to generate power for future energy needs, providing more options than traditional sources. This review offers a comprehensive analysis of how electrospinning technology can be used in energy-autonomous wearable wireless sensing systems. It provides an overview of the electrospinning technology, fundamental mechanisms, and applications in energy scavenging, human physiological signal sensing, energy storage, and antenna for data transmission. The review discusses combining wearable electronic technology and textile engineering to create superior wearable devices and increase future collaboration opportunities. Additionally, the challenges related to conducting appropriate testing for market-ready products using these devices are also discussed.

- Saunders, N., Gunawardhana, K. R. S. D., Magre Colorado, L. A., Baberwal, S. S., & Coyle, S. (2023). Hit the Ground Running—Wearable Sensors to Measure Foot Plantar Pressure. Engineering Proceedings, 30(1), 6.

  Abstract Flexible pressure sensors can be used to predict possible injuries and inform the wearer about their foot posture and landing positions during both walking and running. This work focuses on designing and producing capacitive pressure sensors and integrating them into a smart insole. The suitability of sensors was assessed using a mechanical test rig to measure the change of capacitance under different loads. The effects of introducing micropores into the dielectric layer using two fabrication methods were analysed. The results obtained imply that the use of micropores has the potential to increase the sensitivity and improve the response time of the sensors.

- Baberwal, S. S., Magre, L. A., Gunawardhana, K. R. S. D., Ward, T., & Coyle, S. (2023). Protocol design and testing to investigate Motor Imagery training using cues in different mediums: A pilot study. Proceedings of 20th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE). Mexico City, Mexico. October 25-27 2023.

  Abstract A Brain-Computer Interface (BCI) system converts brain activi-

ties into control signals that could be used to operate an interface such as an exoskeleton. One of the potential brain activities for BCI control is Motor Imagery (MI), i.e. imagination of limb movements. This type of brain activity is most prominent in the Alpha and Beta band. These signals require intensive training that could further be used as enhanced features for classification. Different studies highlight the importance of training by commands/cues presented in mediums such as a computer screen, audio or Virtual Reality (VR). However, as of now, there is little evidence regarding the use of this protocol for comparing the performance of these different training cues. This paper presents not only the design of the protocol but also reports a pilot study performed to evaluate MI signals by presenting cues in three different mediums, i.e. a computer screen, a VR headset, and speakers, studying the signals, extracting features and reporting the accuracy for the left/right classification. The results suggested a significant difference in the Event-Related Desynchronization Synchronization(ERDS) from MI signals of the participants for both alpha and beta bands when the cues were presented in the VR headset, along with the highest classification accuracy for this medium.

- Gibbons, D., Magre, L. A., & Coyle, S. (2023). An IoT-enabled Knee-sleeve for Home Rehabilitation: A Pilot Study. E-Textiles 2023. 5th International Conference on the Challenges, Opportunities, Innovations and Applications in Electronic Textiles. 14th – 16th November 2023. Ghent, Belgium.

  Abstract In this project, a smart knee sleeve was developed for the purpose of measuring a subject's knee angle continually. The device is wireless and washable, making it suitable for rehabilitation at home. Two separate methods were incorporated onto a standard knee sleeve: a flexible silicone-based bend sensor(Bend Labs 2-axis); and two IMUs. The accuracy of both methods was compared to determine the suitability of the Bend Labs sensor which is more compatible for textile integration. The advantages of each approach was evaluated. Testing was done on three subjects wearing the smart garment,

using a reference video method. Squats were used as the exercise protocol for testing. The results showed the flex sensor performed better for two of the three participants, with an average RMSE of 8.3 degrees which is comparable to results from related research.

A.3 Science Communication and Events

- Participation and poster presentation at the Spring School on Social XR. "Smart garments for immersive home rehabilitation using AR/VR". The school took place from March 13-17, 2023 in the Centrum Wiskunde & Informatica (CWI), in Amsterdam, The Netherlands.

- Participation in Research Day DCU. Took place in Dublin City University in Dublin, Ireland, on the 20th of April 2023. "Smart garments for immersive home rehabilitation using AR/VR". Participation in the Thesis in 3 event, which consists of presenting your research in 3 minutes in a lightning session with other researchers.

- Participation and presentation in the Post-CHI Summer School on Extended Reality (XR). "Smart garments for immersive home rehabilitation using AR/VR" The school took place from May 2nd to May 4th of 2023, in Copenhagen, Denmark.

- Presentation at the Women in Research Ireland (WIRI) Research Showcase 2024. "User-centred design of a VR based rehabilitation system- A preliminary study to overcome the barriers of rehabilitation from Anterior Cruciate Ligament Reconstruction". The event took place on March 21st 2024 from 11 AM to 2 PM at UCD University Club.

- Speaker in the d-real XR Seminar: Psychological and physical dimensions of VR applications. "User-centred design of a VR based rehabilitation system - A preliminary study to overcome the barriers of rehabilitation from Anterior

Cruciate Ligament Reconstruction". The presentation took place on April 16th 2024 at Dublin City University.

- Speaker at DCU VIBES (Virtual, Immersive, Blended Education Symposium). "Designing for engagement: Cozy gaming for long term goals". January 10th 2025.

- Speaker at FÍOR '25: Fostering Industry Outreach & Research Collaboration. "Designing for engagement: Cozy gaming for long term goals" February 12th 2025.

Appendix B

Questionnaires

B.1 Feedback Questionnaire: Part A

This is the questionnaire used on the user study of the first iteration of the game

Specific Questionnaire for the application/system

Date:

Participant:

Please, from 1 to 7, circle the response that closely represents your opinion.

1. How comfortable did you feel while wearing the headset?

1	2	3	4	5	6	7
Very uncomfortable	Uncomfortable	Somewhat uncomfortable	Neutral	Somewhat comfortable	Comfortable	Very comfortable

If you experienced any discomfort while wearing the headset, can you describe the feeling further?

2. How stressed did you feel the performance of the task?

1	2	3	4	5	6	7
Very relaxed	Relaxed	Somewhat relaxed	Neutral	Somewhat Stressed	Stressed	Very stressed

Additional comments: _____

3. How confident were you in your movements?

1	2	3	4	5	6	7
Very uncertain	Uncertain	Somewhat uncertain	Neutral	Somewhat confident	Confident	Very confident

Additional comments: _____

4. How easy was it to move around while wearing the headset?

1	2	3	4	5	6	7
Very hard	Hard	Somewhat hard	Neutral	Somewhat easy	Easy	Very easy

Additional comments: _____

5. How engaged did you feel during the experiment?

1	2	3	4	5	6	7
Very disengaged	Disengaged	Somewhat disengaged	Neutral	Somewhat engaged	Engaged	Very engaged

Additional comments: _____

6. How likely is it that you would use this type of game to do your daily exercises?

1	2	3	4	5	6	7
Very unlikely	Unlikely	Somewhat unlikely	Neutral	Somewhat likely	Likely	Very likely

Additional comments: _____

Other comments/suggestions on the system: _____

B.1.1 Feedback Questionnaire: Part B

Please circle the answer that is closest to your personal experience:

1. **Do you have experience using Virtual Reality?**
   (a) Yes, I own a headset and use it frequently
   (b) Yes, I have used it several times
   (c) Yes, I have used it once or twice before
   (d) No, I have never used Virtual Reality

2. **What level do you partake in sports/fitness activities?**
   (a) Professional athlete
   (b) Amateur athlete
   (c) Occasionally play sports or attend gym
   (d) Other, please specify:

3. **Have you undergone an Anterior Cruciate Ligament Reconstruction (ACLR) surgery?**
   (a) Yes
   (b) No
   (c) No, but I had a different injury that required surgery

4. **If you answered 'yes' to the previous question, how long ago did you have surgery?**

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