École Polytechnique Fédérale de Lausanne

Pilot study on the feasibility and usability of a rehabilitation system using a lower-limbs exoskeleton and virtual reality games

by Nicolas Vial

Confidential

Master Thesis

Dr. Amalric Ortlieb
Autonomyo Supervisor

Prof. Dr. Ronan Boulic
EPFL Supervisor

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Abstract

This study explores the use of virtual reality (VR) in the field of rehabilitation, specifically focusing on home-based rehabilitation. With the primary goal of assessing the potential impact on motivation and engagement between a rehabilitation video game and a repetitive exergame, a VR rehabilitation system incorporating a lower limb exoskeleton was developed. The system integrates a rehabilitation video game designed to resemble a traditional video game while incorporating rehabilitation mini-games. The feasibility and usability of the system, as well as specific design choices such as implementing static walking or a virtual interface interaction system without the need for controllers, were evaluated through testing involving 10 healthy participants, including physiotherapists. The findings suggest a significant potential for the rehabilitation game to enhance patient motivation and engagement. While the system demonstrates feasibility for home-based rehabilitation, the sub-optimal comfort level and identified areas for improvement within the mini-games and static walking segments underscore that the system's usability is not yet fully conducive to effective rehabilitation.

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Chapter 1

Introduction and motivations

In this chapter, the work carried out during this study is presented. The first section provides background information on the topic of using virtual reality (VR) in rehabilitation, along with the reasons for developing the system described in this study. The following section introduces the system and outlines the objectives of this study. The final section outlines the structure of this paper.

1.1 Background and context

Virtual reality has emerged as a new tool in the field of rehabilitation, transforming the way patients recover from various physical and cognitive impairments. This new technology allows the creation of immersive computer-generated environments that simulate real-life experiences, offering a wide range of therapeutic applications. One of the main advantages of VR advanced by studies on the subject is its ability to provide personalized, engaging experiences. Therapists can design custom environments and activities that challenge patients at their specific levels of ability. The use of VR in rehabilitation has also brought improvements in motivation and engagement during therapy sessions. Traditional rehabilitation exercises can often be repetitive and monotonous, leading to reduced patient adherence. VR addresses this challenge by turning therapy into an interactive and enjoyable experience, motivating patients to actively participate in their recovery.

The conducted studies are nonetheless subject to limitations, which are the reasons for creating the system described in this study. One primary limitation is the fact that the developed rehabilitation games tend to be overly repetitive and fail to effectively address the issue of patient motivation and engagement over the medium and long term. A second limitation is the remarkable absence of focus on home-based rehabilitation in nearly all studies, with very few systems being adaptable to such an environment, primarily due to spatial requirements or the essential quantity of tools necessary for these systems to function effectively. This study takes into consideration the use of an exoskeleton named "Autonomyo," which has been developed in part with the intention of being used for home-based rehabilitation. The entire system has been designed and developed to be suitable for home rehabilitation.

1.2 System and objectives

The system comprises three main components. The first is the lower limb exoskeleton (see Figure 1.1), primarily used in this study for tracking knee and hip angles as well as abduction, with the long-term goal of providing the necessary assistance for users to perform desired movements. The second component is the Oculus Quest 2 virtual reality system, housing the rehabilitation games developed in this study and communicating with the exoskeleton to create a full-body avatar for in-game full-body tracking. The third and final component is employed to offer support to the user, minimizing the risk of imbalance and falls. Initially, crutches were used throughout the development phase, later replaced by a safety frame that offers enhanced support while allowing hands-free interaction by leaning on the parallel bars of the frame.

Figure 1.1: The Autonoymo exoskeleton

This system was developed with the intention of being usable for home-based rehabilitation and for other purposes as well. One of these purposes is to understand the impact on motivation and engagement of the rehabilitation video game developed in this study, compared to the repetitive exergames commonly employed. Other objectives revolve around establishing best practices for a system like this and testing various design choices, such as implementing a static walking system or a means of interacting with the virtual interface.

1.3 Structure

The structure of this document begins by providing an overview of the current state of the art concerning the use of VR in rehabilitation, both with and without exoskeletons, as well as an exploration of games developed through recent studies. This discussion serves to delineate the limitations of these studies and introduces the developed system. The subsequent chapter delves into the design and methodologies employed. It starts with an introduction to the exoskeleton and its diverse sensors, followed by an introduction to the concept of VR embodiment and the use of a full-body avatar. The ensuing section elucidates the method of interaction with the interface, developed to avoid the need for controllers. Subsequently, the primary rehabilitation exergame, along with a rehabilitation video game encompassing various mini-games and static walking scenarios, is presented. Concluding this chapter, the ultimate segment provides a detailed exposition of the pilot test protocol, encompassing the selection and participation of test subjects, as well as the use of the safety frame for the tests. The next chapter will present the results, first on cybersickness and then on usability, before discussing these results and concluding in the final chapter of this study.

Chapter 2

State of the art

This chapter describes how other works address the various challenges of using immersive virtual reality (IVR) for rehabilitation. Section 2.1 looks at different approaches and technologies used in rehabilitation that make use of virtual reality (VR). The first part focuses on approaches that do not use exoskeletons and then presents approaches that combine VR and exoskeletons to come closer to systems similar to the one in this study. The next section will focus on different rehabilitation games that have been developed in VR. The final section of this chapter highlights the potential limitations of the work done in this field, before finally introducing the rehabilitation system described in this study.

2.1 Rehabilitation using virtual reality

The use of virtual reality in rehabilitation has been evaluated and tested for several years using a variety of systems, aiming to determine its efficacy and effectiveness. These efforts have also aimed to identify optimal practices for its implementation in different types of rehabilitation within this domain. Demeco et al. [1] conducted a systematic review in 2023 exploring the application of immersive virtual reality in stroke rehabilitation. The outcomes of this review revealed additional benefits for both upper and lower limbs when compared to or integrated with standard rehabilitation methods. The study further concluded that IVR could be advantageous due to positive patient evaluations, tolerability, suitability for clinical practice, minimal adverse effects, and the ability to customize interventions based on individual adherence levels. The integration of IVR with standard care rehabilitation has yielded positive outcomes. For instance, combining IVR with mirror therapy or treadmill gait training has led to improved recovery of upper limb function and enhanced gait parameters. IVR has also exhibited the potential in augmenting cognitive-based strategies, such as action recognition and motor imagery, which can contribute to the comprehensive representation of gait patterns. Additionally, IVR has demonstrated medium-term effects in reducing post-stroke depressive symptoms, increasing motivation, and diversifying neurorehabilitation approaches.

2.1.1 Systems without exoskeleton

An investigation into the use of VR without the use of an exoskeleton was conducted by Cortés-Pérez et al. [2] with the objective of assessing the effectiveness of IVR therapy in comparison to conventional therapy for stroke rehabilitation, specifically focusing on balance improvement and fall prevention. The study employed the HTC Vive motion-tracking system and incorporated four pre-existing immersive games that were not specifically designed for rehabilitation purposes. The findings indicate that immersive VR therapy holds significant promise as a valuable intervention for addressing balance disorders in individuals with chronic ischemic stroke, and it can be seamlessly integrated with traditional physiotherapy approaches.

Fregna et al. [3] have developed their own IVR game and system for upper limb rehabilitation. The used system incorporates the Quest 2 VR head-mounted display (HMD) and a client application running on a PC that communicates with the headset to facilitate the rehabilitation session (see Figure 2.1). The selection of this particular HMD was based on several technological factors, primarily due to its real-time hand-tracking capability. Through the client application, therapists can observe and manage the patient's actions and assigned tasks. Furthermore, the system has been designed to enable remote rehabilitation sessions to be conducted from the comfort of the patient's home. Four specific tasks have been developed to closely replicate the movements typically performed during traditional rehabilitation sessions.

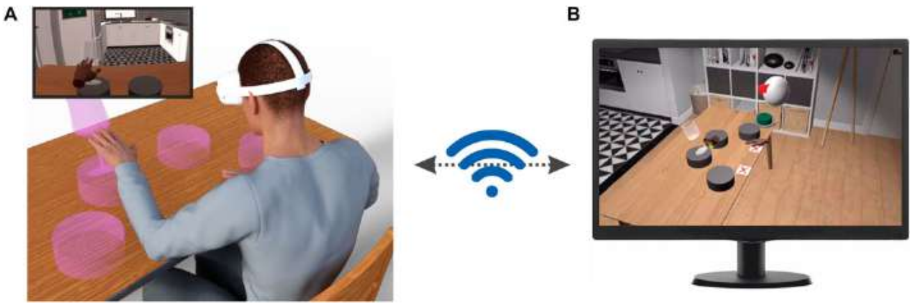
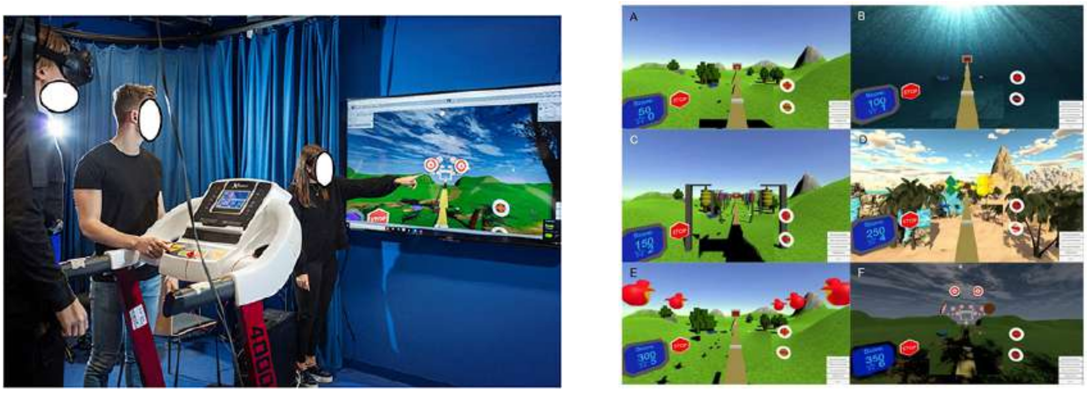


Figure 2.1: Application scenario of the IVR environment in the study by Fregna et al. [3]. (A) The patients are immersed in a VR environment by means of an HMD where they can see different objects with which they can interact. (B) The program communicates with a client app running on a PC that allows to monitor remotely and in real-time the patients' behavior, set their rehabilitation routines, and vocally interact with them.

The pilot study conducted by Moan et al. [4] was set up to investigate whether stroke survivors can safely use immersive virtual reality with modern HMDs while walking on a treadmill, and study their and clinicians' experiences to assess acceptability and potential for rehabilitation. The system used includes an HTC Vive VR headset, a treadmill, a 3D motion capture system, and a safety harness in case of loss of balance or fall (see Figure 2.2). The user's feet are continuously tracked and displayed in the virtual world using reflective markers attached to the feet. The exercise used is called “VR-mill” and consists of 6 mini-games, the first two of which are used to familiarize the user with walking on the treadmill while wearing VR equipment and to define the user’s preferred speed for the workout since the walking speed in the game is synchronized with the speed of the treadmill. The game also includes a treadmill position display, enabling participants to locate the treadmill handrails and hold on to them during exercise.



(a) VR-mill game setup

(b) Screenshots from all six mini-games

Figure 2.2: The setup and 6 mini-games used in the study by Moan et al. [4]

Treadmills are often used in walking rehabilitation, which is why many studies have looked at the use of treadmills combined with virtual reality. This is the case of the feasibility study by Brandín-De la Cruz et al. [5] which uses an anti-gravity treadmill system comprising a treadmill, a body-weight support, and a VR headset used with two controllers. The task is to walk in an immersive environment and move forward by moving both joysticks forward at the same time or in the desired direction.

Before moving on to the section using exoskeletons, some studies have come closer by using a robot-assisted walking device. This is the aim of a paper by Hamzeheinejad et al. [6] which tested a system using a robot-assisted walking device combined with VR. Before this objective can be achieved in future work, the system used did not yet include a robot-assisted walking device, but a cross-trainer. The headset used was an HTC Vive, and sensors attached to the cross-trainer tracked foot movement. The headset controllers were attached to the cross-trainer to enable the user to grip the cross-trainer handles. The virtual environment consisted of natural landscapes where walking movements were mapped into the virtual environment to simulate walking.

Another study that used a system containing a robot-assisted walking device is that of Morizio et al. [7] The system used contains a complex gear system allowing a walking-like movement with two foot plates and partial or total body weight support, as well as an HTC Vive VR headset. An HTC Vive sensor placed on the participant’s right foot collected the walking movement in order to implement a synchronized movement of the in-game avatar. An application was also developed for the therapist, providing real-time access to the virtual environment and the patient's clinical data (see Figure 2.3). The task performed in the virtual environment was to walk in a straight line in different natural environments. The aim of the study was to evaluate the occurrence of cybersickness, the feeling of presence, and the ease of use of the system. To this end, questionnaires were used, notably the Simulator Sickness Questionnaire (SSQ) to assess the onset of cybersickness.

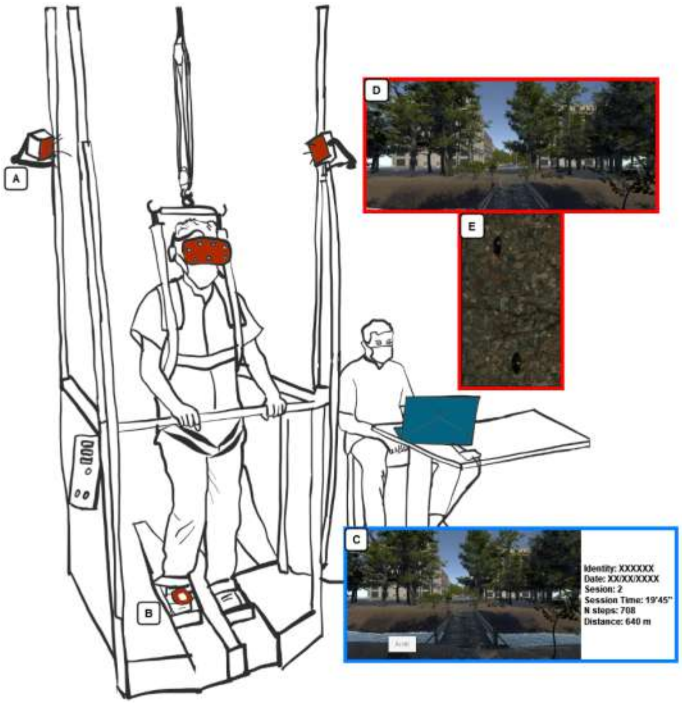


Figure 2.3: The setup used in the study by Morizio et al. [7]. (A) HTC Vive station base; (B) HTC Vive Sensor; (C) view of therapist; (D) view of the participant; (E) participant's feet from participant view.

2.1.2 Systems with exoskeleton

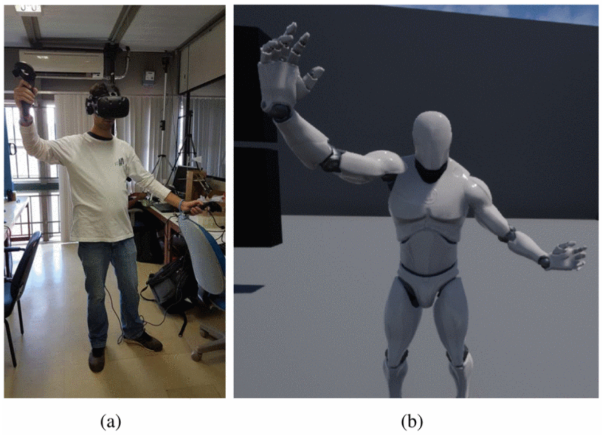
Exoskeletons, being a means used in rehabilitation, and virtual reality, a recent and promising tool in this field, have been the subject of studies combining these two technologies. A systematic review conducted in 2019 by Mubin et al. [8] on the subject of exoskeletons and VR shows that few studies have been conducted with these technologies for lower limb rehabilitation compared to upper limb rehabilitation. Additionally, the exoskeletons used are often very different from one another. Another observation made is that these exoskeletons and systems are rarely available for home trials, highlighting a significant gap in transitioning rehabilitation services from a clinical setting to a home environment.

Hamzeheinejad et al. [9] decided to add VR to an existing system used for gait rehabilitation, in order to test the impact of implicit and explicit feedback on performance and experience. The rehabilitation system used was the driven gait orthosis Lokomat [10], consisting of a treadmill with adjustable handrails, a weight support system with a support rope and frame, a gait orthosis, and a patient screen for feedback. The VR part consists of an HTC Vive headset and two HTC trackers attached to the Lokomat orthosis. The virtual environment represented different natural landscapes, and the translation of the virtual scene moved in accordance with the patient's walking speed. Thanks to trackers, an embodiment avatar was created using inverse kinematics to enable patients to see virtual legs move in accordance with their actual movements. A virtual trainer was developed to provide explicit feedback for users (see Figure 2.4). To test whether users suffered from cybersickness or undesirable side effects, the study used the SSQ before and just after therapy.

Figure 2.4: The setup used in the study by Hamzeheinejad et al. [9]. Top left: participants were exposed to the VR simulation while using the gait robot (Lokomat). Top center: avatar embodiment. Virtual handles (in light blue) mimic the position and shape of the real physical handles to generate plausible hand actions during walking. Top right: explicit visual feedback signaled at the trainer's feet. Bottom left: same explicit feedback signaled at the patient's feet. Bottom center: alternative feedback example. Bottom right: emoticon feedback.

De Sousa et al. [11] focused more specifically on user embodiment using a VR avatar. The system used included an HTC Vive headset for head tracking and controllers for hand tracking. Inertial measurement units (IMUs) attached to the user's legs and thighs were used for leg tracking. All these live positions were used by an inverse kinematics algorithm to move a first-person avatar replicating the user's movements (see Figure 2.5). The system has been designed for use with an exoskeleton, treadmill, and body-weight support system, enabling the patient to stand and walk while remaining in place.

(a) IMUs tracking the movement of the left thigh and leg of the user while the avatar replicates the movement



(b) The avatar arms and hands being moved by tracking the position and orientation of the motion controllers at the hands of the user

(c) First person perspective of the avatar body

Figure 2.5: The setup used to obtain a full-body avatar in the study by De Sousa et al. [11]

2.2 Virtual reality games in rehabilitation

Video games are constructed upon various game design elements that serve as the foundation for creating an engaging experience. However, some of these elements are either inapplicable or challenging to implement in the realm of rehabilitation. For instance, caution must be exercised when incorporating competition and score-based confrontation, as certain physical limitations resulting from a patient's condition might prevent them from attaining specific scores. Confronting patients with unattainable scores could lead to frustration, which is undesirable. The field of rehabilitation brings forth numerous limitations, particularly in the context of walking rehabilitation. These limitations account for the striking similarities among most games developed for this specific domain, often rendering the term "video game" ill-suited. Studies in this field typically use rehabilitative exercises as the foundation for their games. Two prominent types of exercises emerge for walking rehabilitation: games involving specific leg movements and games that solely involve walking. These games exhibit varying degrees of game design complexity, and they can be categorized as follows:

- Activities with little or no game design principles, closer to an exercise than a video game.
- Activities that have been gamified using game design principles.

An example in the first category comes from the study by Huihui Cai et al. [12], which used four scenarios set in different virtual reality landscapes (see Figure 2.6). One of these scenarios requires the patient to step over wooden bars with adjustable heights, while another asks the patient to climb stairs in the virtual world (see Figure 2.6). These games use very few game design principles and are exercises that could be performed in real life, with VR mainly providing the ease of creating immersive worlds in which to perform an exercise, as well as the ease of modifying different parameters.

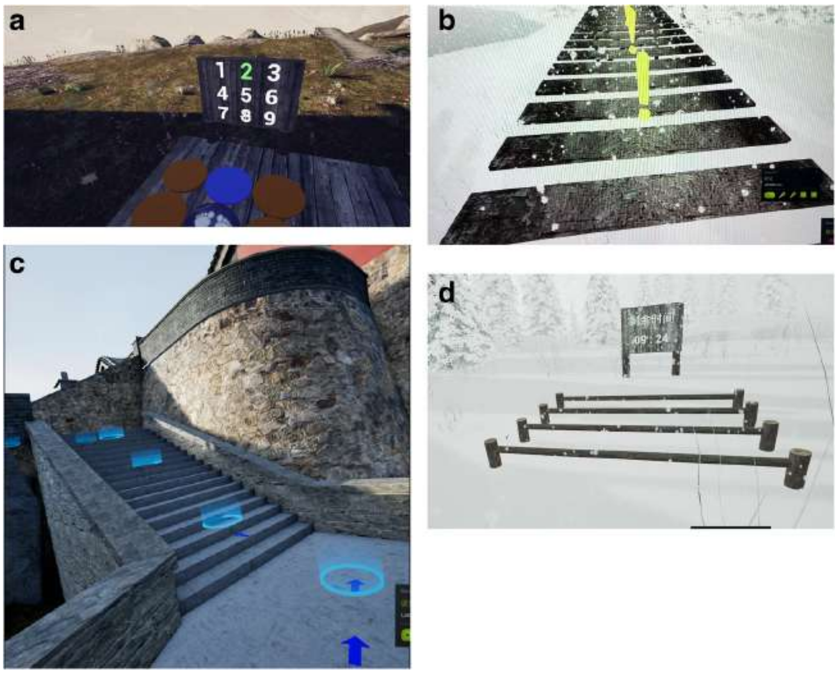


Figure 2.6: The 4 scenarios used in the study by Huihui Cai et al. [12]

One of the studies that made the most use of gamification to increase motivation was that by Kern et al. [13], who gamified a simple exercise often performed in rehabilitation: walking in a straight line. To achieve this, game design principles such as a reward system, auditory and visual feedback, a storyline, good sound design, and a visual identity were used (see Figure 2.7). Other studies have also gamified various exercises to varying degrees, often with the aim of enhancing user enjoyment, motivation, and engagement [14, 15, 16, 17].

Figure 2.7: The game created for the rehabilitation system used in the study by Kern et al. [13]

However, despite incorporating a wealth of crucial game design elements, these games don't neatly fit within a singular genre. The genre bearing the closest resemblance is that of life simulation, primarily due to the performed movements and the frequent depiction of environments that mirror real-world landscapes, such as walking scenarios. Numerous factors contribute to the challenge of categorizing these games within a traditional genre. One pivotal factor is the absence of a distinct game-play mechanism, alongside the dearth of objectives that drive narrative advancement or the unlocking of in-game elements. Above all, these games lack a definitive conclusion, making them inherently repetitive, since each new session essentially entails the same gameplay, albeit presented at varying levels of difficulty. Notably, the elements that commonly foster heightened motivation and engagement, including a tangible sense of progression, unlocking new content, and the inherent desire to replay in order to pick up where one left off, are notably absent in the current landscape of rehabilitation games.

2.3 Limits of the current approaches

Current approaches have made it possible to obtain encouraging results and information on good practices in the use of immersive virtual reality in rehabilitation, but there are still limitations that explain the creation and study of the system described in this paper.

The first limitation to note is the gamification of rehabilitation exercises. Some studies use a lot of game design principles to make an exercise more motivating and enjoyable, and the results in this goal are encouraging but obtained in the short term and in clinical conditions. In addition, Rehabilitation games focus on certain movements in particular, so there is little freedom in the creation of different rehabilitation games which explains the lack of variety and repetitiveness during rehabilitation sessions. This repetitiveness could cause patients to lose motivation and commitment when rehabilitating at home over the medium and long term. That's why this study describes the development of a rehabilitation game closer to a classic video game, integrating different rehabilitation games to avoid repetition and incorporating a short story, a goal to achieve, and the possibility of moving around in a virtual world.

Another limitation of studies on walking rehabilitation is the impossibility of moving from clinical rehabilitation to home rehabilitation, often due to the size and implementation of the system. The system described in this paper has been designed and implemented to allow both clinical and home use.

These limitations are the primary reasons for implementing the system described in this study. The system, detailed in the next chapter, includes a lower-limbs exoskeleton, a safety frame to provide support and security to the user, and a VR rehabilitation video game featuring various exergames, walking in place, and a complete avatar of the user.

Chapter 3

Design and Methods

In this chapter, we will delve into the system design and the methods employed, beginning with an overview of the exoskeleton and its integration within the system. Moving forward, the following chapter explores the implementation of VR embodiment, using the diverse sensors available in the system. Section 3.4 describes the main rehabilitation game, which serves as the core component around which other games and tools were integrated to construct the rehabilitation video game described in section 3.5. Lastly, the concluding section of this chapter details the setup of the pilot tests and the selection criteria for the participants.

3.1 Exoskeleton

The exoskeleton used in this study is known as "Autonomyo" (see Figure 3.1), developed by a startup bearing the same name. Autonomyo is a lower-limb exoskeleton designed to grant users a high degree of freedom in movement. Its primary purpose is to enable individuals with muscular and neurological impairments to regain the ability to walk. Additionally, it incorporates an intelligent assistance controller that considers the user's present capabilities, thus providing the necessary assistance for optimized training. However, as this part is still in the development phase, only the "transparent" control mode has been used. In this mode, the exoskeleton supports its own weight but doesn't offer any additional assistance. The exoskeleton was designed with the purpose of being suitable for home rehabilitation use.

(a) The exoskeleton joints

(b) The exoskeleton worn by a user

Figure 3.1: Images of the Autonomyo exoskeleton when empty and in use.

The next section presents the various Autonomyo sensors used in this study, before describing the surface of the exoskeleton's communication system, which sends data to the virtual reality HMD in the case of this study.

3.1.1 Sensors

A first set of sensors is situated on the exoskeleton's two soles, with each sole equipped with 8 force sensors that provide real-time information on the force applied to each cell (see Figure 3.2). This data is extensively used in the application for both the balance game and embodiment purposes, as will be elaborated upon later. Additionally, there are six other inputs: the angles at the knees, hips as well as the abduction angles which serve as essential elements in the primary rehabilitation exergame and embodiment functionalities (see Figure 3.3).

Figure 3.2: The soles are each equipped with 8 force sensors, providing real-time information on the force applied to each cell.

(a) Knee angle tracked by the exoskeleton

(b) Hip angle tracked by the exoskeleton

(c) Abduction angles tracked by the exoskeleton

Figure 3.3: The exoskeleton tracks the angles of the knees, hips, and leg abduction, which are then employed in the rehabilitation exergame and to generate a full-body avatar of the user.

Autonomyo includes other sensors, such as an inertial measurement unit (IMU) located on the back. However, these sensors are not used in the application, and their details will not be further developed here.

3.1.2 Communication

In order to understand the communication between the exoskeleton and the application, it is not necessary to grasp all the architectural details. Therefore, many details will be avoided to focus only on what is necessary to understand the communication of the system.

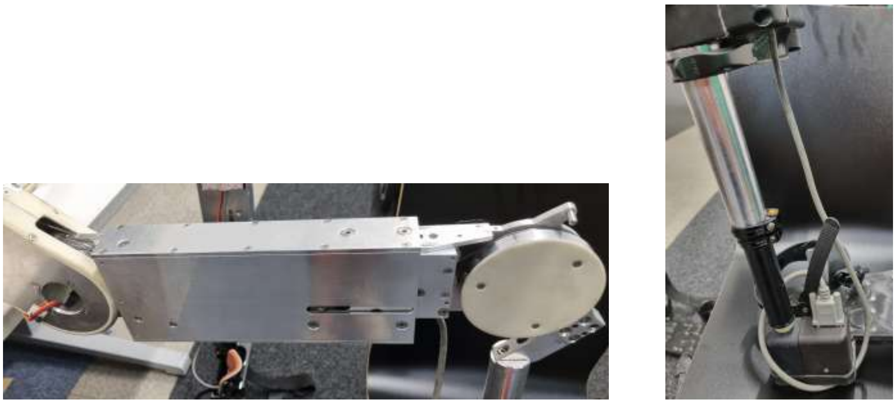
The initial step is to power on the exoskeleton, activating a Wi-Fi signal emitted by a Wi-Fi USB key situated at the device's rear. To establish communication and control Autonomyo, it is necessary to launch a program by connecting to the exoskeleton via the SSH protocol [18] from an external computer. This grants access to the exoskeleton's files, including the required program. This program performs several operations, including launching a TCP server enabling direct and bidirectional communication with the exoskeleton.

The application can then be launched, taking care to ensure that the VR headset is properly connected to the exoskeleton's Wi-Fi, allowing communication via the TCP protocol. Once the application is running, it creates a TCP client that, once connected to the device, first receives the list of accessible variables from the exoskeleton before being able to communicate freely to obtain or send the necessary information for the proper functioning of the application.

The application can request to receive values periodically automatically or ask for values when needed. The values requested periodically are those discussed in 3.1.1, which are required continuously in the application. However, values that allow, for example, turning on or off the motors, calibrating the abduction, or calibrating the force sensors of the soles, are only sent a few times at specific moments and, therefore, are not sent periodically but requested when needed by the application. Once the connection protocol is completed, the application sends a list of values it wants to receive periodically, and the server sends them at a frequency of 10 times per second.

3.1.3 Set up

Prior to the user entering the exoskeleton, a setup is required. Firstly, the length between the ground and the axis of knee rotation, as well as the length between the axis of knee rotation and the axis of hip rotation, must be calculated. The different parts of the exoskeleton need to be adjusted based on these measurements before attaching it to the user (see Figure 3.4). This setup process typically takes between 5 and 10 minutes.



(a) The femur of the exoskeleton

(b) The tibia of the exoskeleton

Figure 3.4: The length of the exoskeleton's femur and tibia must be adjusted to the length of the user's lower limbs for optimum use.

Once the external setup of the exoskeleton is complete, the remaining calibration takes place within the game. Upon entering the application, the user needs to calibrate the force sensors in the soles as well as the abduction of the exoskeleton by pressing buttons displayed on the application's interface (see Figure 3.5). Another crucial calibration required for optimal gameplay is the calibration of the avatar. This calibration ensures the correct alignment of the avatar's head and body when the user stands straight and looks straight ahead, providing a consistent visual experience.

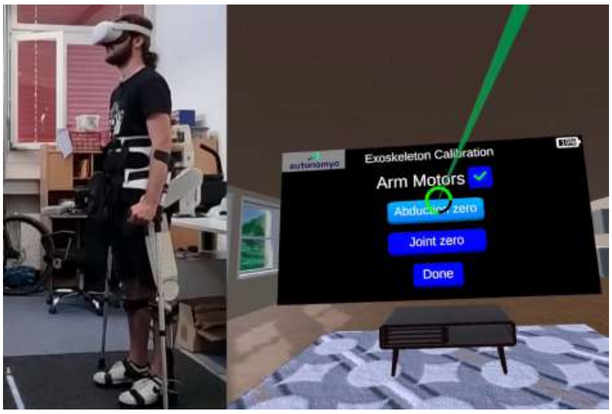


Figure 3.5: The user is completing the calibration phase within the application. He is setting abduction to 0 while standing upright.

However, a limitation of this system is that the calibration may become inaccurate if the user turns or moves, as only the head will move, not the legs unless the walking mode is activated. Consequently, this can result in inconsistent visual feedback. To address this, the avatar re-calibration is possible at any time if needed by simply doing a thumb-up with the left hand while looking straight ahead.

The complete setup of the system may take between 15 to 20 minutes, with the majority of this time attributed to the calibration of the exoskeleton, which is still in its developmental phase and will consequently be refined in the future. On the other hand, the setup time for the VR component is extremely rapid (< 2 minutes), involving simply connecting the headset to the exoskeleton, launching the application, and establishing a connection within the application once initiated.

3.2 VR Embodiment

The sense of embodiment in VR is defined as the feeling of being inside the body (ownership), where the body is (location), and moving the body according to one's own intentions (agency) [19]. Research has shown that inducing this sense of embodiment can significantly accelerate motor rehabilitation compared to non-embodied experiences, and it also correlates positively with the overall rehabilitation outcome [20, 21]. To enhance this sense of embodiment and presence, recent studies have increasingly used avatars to represent patients in VR rehabilitation [7, 10, 11]. By adopting an avatar representation, patients can observe themselves in real-time through mirrors or third-person views, thus facilitating their interaction with the virtual world. This study follows a similar approach, employing a full-body avatar system, the details of which will be described in the following section.

3.2.1 Avatar

Various tools were employed to create a complete avatar without the need for physical devices other than the VR headset and exoskeleton. The primary goal was to simplify the setup and achieve a "plug-and-play" system to facilitate home rehabilitation while maintaining high-quality tracking to ensure a seamless user experience. To represent the user, a humanoid visual was needed, and the design chosen came from Sunbox Games' "Stylized Customizable Avatars FREE" asset, available from the Unity asset store. This asset of visuals was chosen over the one provided by the QuickVR library for its resemblance to a human being, and for the possibility of customizing them to create secondary characters in the rehabilitation video game, ensuring a consistent visual identity (see Figure 3.6).

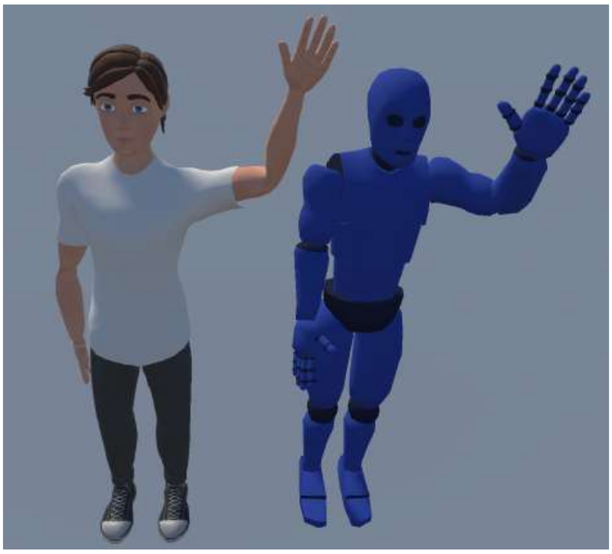


Figure 3.6: On the left, the avatar used for the game, and on the right the avatar supplied by the QuickVR library.

The most commonly used technique for animating the avatar when specific body parts are tracked is inverse kinematics [22, 23]. This approach enables the avatar to present coherent movements throughout the body, even if only certain specific points, such as hands or feet, are tracked. To achieve this, our study used the QuickVR standard library [24], which provides virtual character representation. However, since the avatar visuals proposed by QuickVR did not resemble a Human, they were replaced in this study by the visuals described above. This library facilitates consistent avatar movement by incorporating values from the different tracked points.

To obtain an avatar that precisely mimics movements, tracking as many points as possible is necessary, which is not easy without using trackers placed on the user's body. However, this study does not employ trackers placed on the user's body. The points and tracking methods are further detailed in the following chapter.

3.2.2 Movements tracking

The VR headset and exoskeleton track the following points: Head, hands, hips, and knees. The following subsections describe how each point is tracked. As tracking the hips and knees also provides information on the position of the feet, these three points are grouped together in section 3.2.2.3.

3.2.2.1 Head tracking

The head is tracked using the Oculus Quest 2 headset, which features a pose-tracking system using 4 infrared cameras to detect the precise position of the HMD in Euclidean space. This tracking system is often referred to as 6DOF (degrees of freedom) tracking. The user's vision in the headset is positioned to see into the avatar's eyes, thanks to the Oculus XR plugin and QuickVR library (see Figure 3.7).

3.2.2.2 Hands tracking

Hand tracking uses the same tracking system as head tracking. The HMD Analyzes hand images using the sensors on the headset to precisely determine the positions of specific key points on the hands, such as the knuckles or fingertips. This real-time analysis occurs directly on the device while the hands are in motion. The movement of the user's hands moves the avatar's hands, thanks to the Standard Unity Package provided by Oculus and QuickVR (see Figure 3.7).

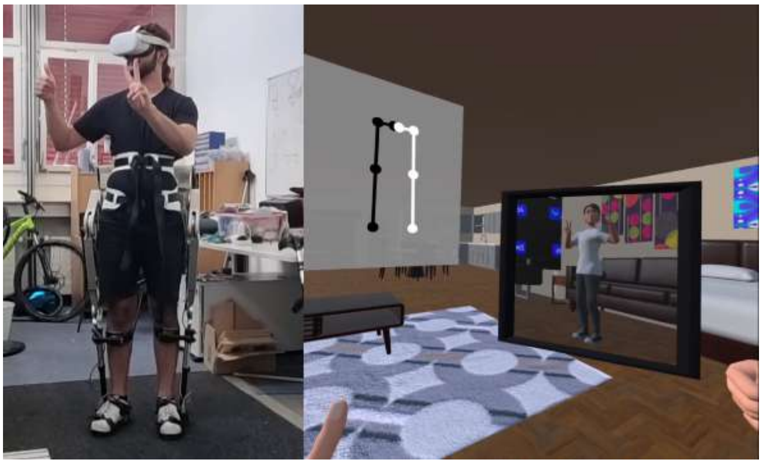


Figure 3.7: The VR headset captures head and hand movements, which are then transmitted to the avatar to ensure consistent upper body tracking.

3.2.2.3 lower limbs tracking

The two sections above offer a simple and effective method for tracking the upper body without the need for a complex external system. That's why it is increasingly being used in rehabilitation. However, since the primary goal of the system is to rehabilitate the lower limbs, it is crucial to also track the lower body while maintaining simplicity and a "plug-and-play" system.

The approach used to track the lower limbs is based on previous methods employed during the creation of various 2D rehabilitation games using the same exoskeleton. These games did not involve moving avatars but displayed real-time frontal and sagittal views of the user's lower limbs (see Figure 3.8). To achieve this, the technique involves using the 6 angles provided by the exoskeleton (knees, hips, and abduction), the length measurements of different parts of the exoskeleton, and trigonometry to calculate the positions of the knees and feet relative to the hips.

(a) Sagittal and frontal planes of the raised right knee.

(b) Sagittal and frontal planes of the outstretched right leg.

(c) Sagittal and frontal planes of the abducted left leg.

Figure 3.8: The frontal and sagittal planes of the lower limbs were used to create a 3D model, which was then used to animate the lower limbs of the avatar.

The planes represent different views along two axes, with the top-bottom axis in common. The 3D tracking was achieved by combining these two planes. However, QuickVR's avatar system only considers 6 control points: the head and both hands tracked using the headset, both feet and a single point for the hips located at the midpoint of the body and at hip height. The calculations used for tracking the hips produce two values (one for each angle), which are then combined to determine the central position. This allows the avatar to move as closely as possible to the user's movements.

A problem arose due to using an approach developed for displaying lower body movements in 2D rehabilitation games. The positions found for the knees and feet are relative to the hip position. As a result, it was challenging to distinguish between a user bending down and lifting both legs, leading to the inability to adjust the hip height, which was considered fixed in the system used (see Figure 3.9).

(a) Upright position with right knee up.

(b) Position with right knee bent and left leg straight.

Figure 3.9: While positions (a) and (b) are distinct, the representation in the frontal and sagittal planes appears identical due to the consistent alignment of the knees and feet with respect to the hips.

To address this issue, the assumption that the user cannot lift both legs simultaneously was used. With this hypothesis, it became possible to differentiate between various cases and adjust the hip position accordingly, using sensors that had not been employed before: the sole force sensors. These sensors can determine if a foot is on the ground or not by summing the forces exerted on all cells of a sole and checking whether this sum is below or above a certain threshold. The two cases considered for determining how to move the hip position are as follows:

- Case 1: No legs up
  If the sole sensors indicate that both feet are on the ground and a height difference is observed in the system that determines the foot position relative to the hips, it means that the hips are moving upwards or downwards. The displacement distance used is the same as the distance covered by the foot in relation to the hips.

- Case 2: One leg up
  If the sole sensors detect that one foot is in contact with the ground and a height difference is noticed in the system that measures the grounded foot position relative to the hips, it indicates that the hips are moving upwards or downwards. The displacement distance used is the same as the distance covered by the grounded foot in relation to the hips.

This solution, in conjunction with the combination of sagittal and frontal planes, was employed to achieve lower-body limb tracking using data exclusively from the HMD, the exoskeleton, and inverse kinematics. However, the system does possess certain limitations and areas for improvement. For instance, a significant challenge lies in the need to adjust the exoskeleton's limb lengths in the code for each new user, which contradicts the system's intended "plug-and-play" ease of use. In this study, average limb lengths were adopted and set to avoid the need for constant manual adjustments, resulting in minor visual discrepancies in the avatar's appearance.

Another limitation arises from using sole force sensors to determine whether to raise or lower a foot or the hips. This approach requires precise calibration of the force sensors to prevent inaccuracies in visual feedback. Moreover, the use of a fixed force threshold fails to account for variations in user weight, potentially leading to errors across different participants.

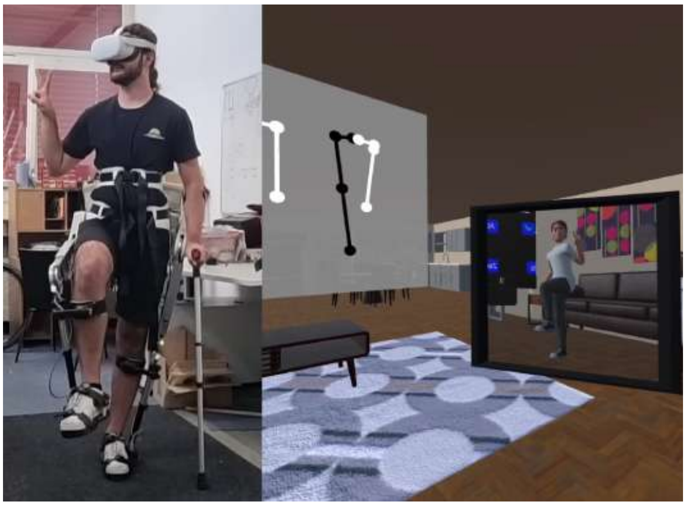


Figure 3.10: Image of complete tracking to obtain a coherent full-body avatar.

Despite these limitations, the system enables the creation of a comprehensive avatar that faithfully represents all user movements without the need for external tools requiring additional setup, ensuring a user-friendly and efficient experience (see Figure 3.10).

3.3 Virtual environment interactions

In order to navigate menus and interfaces, or simply interact with the virtual world, it is essential to have a means of interacting with this environment. The most commonly used method is the use of controllers, which allow users to interact with the environment through the use of buttons in a straightforward manner. However, this method of interaction is not ideal for the system studied in this research, for several reasons. Firstly, holding the controllers requires the patient's hands, but their hands are needed for maintaining balance using crutches or a safety frame, or even playing rehabilitation games, which can be impractical or uncomfortable if they also have to hold the controllers. Secondly, using controllers may not be intuitive for patients, as they must learn the functions of each button and how to navigate through menus, adding cognitive efforts that are best avoided. It is primarily for these reasons that an alternative interaction system has been developed.

The idea is to have a laser pointer extending from the user's head, enabling them to interact with interface elements simply by looking at them (see Figure 3.11). When the laser pointer encounters an interactive element, such as a button, a green gauge gradually fills up until it is filled after 1.5 seconds, and that's when the button is pressed. This simple system has been designed to be highly intuitive and user-friendly, allowing the user to have their hands free for greater comfort.

(a) The pointer does not aim at a button, so nothing happens

(b) The pointer targets a button and the loading bar is visible in green

Figure 3.11: The laser pointer originates from the user's head and aligns with the user's line of sight. The pointer allows the user to press buttons by aiming at them for a certain duration.

Another means of interaction, implemented through the QuickVR library, utilizes hand tracking to recognize certain hand positions, such as thumbs up, thumbs down or touching the thumb with the index finger, enabling interaction with the virtual world. However, this tool was only used to calibrate the avatar, as explained in section 3.1.3, as it is not necessarily intuitive and is not required apart from the avatar calibration, which is performed by the QuickVR library.

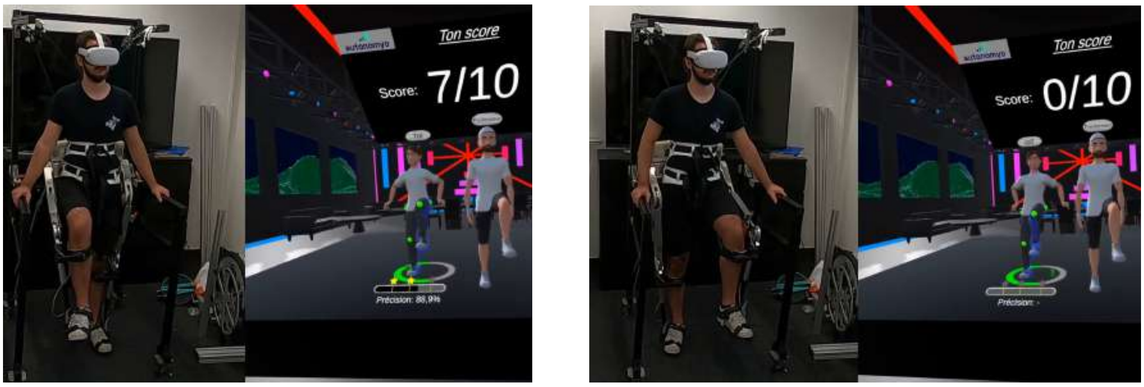
These two methods of interaction are sufficient since the application has been developed to minimize the interactions required by the user with the environment.

3.4 Main rehabilitation exergame

The main rehabilitation game is a repetitive exergame in the style of a dance game, where the user is required to imitate the movements of an avatar positioned in front of them. The choice of this game was primarily due to its ability to prompt the user to perform any movement, allowing for personalized exercises for each patient. The ease and speed of adding movements to the game according to the patient's needs further supported this decision. The game interface was designed based on the game "Just Dance", featuring a representation of the user facing themselves with the avatar to imitate (the teacher) placed next to them. The objective of the game is to mimic the teacher's positions and hold the correct position for approximately 1 second to validate and proceed to the next position. The game ends after completing ten positions. To assist the user in positioning correctly, a display of the position to imitate has been added in transparent blue over the user's avatar (see Figure 3.12).

Figure 3.12: During the dance game, the user is required to lift one leg, and the position to mimic is displayed as a transparent blue outline on the player.

During the game's development, a question arose: Should the user imitate the teacher's movements in a mirrored or anatomical way (see Figure 3.13)? For instance, if the teacher raises their left leg, should the user raise their right leg (mirrored) or their left leg (anatomical)? To address this question, it was decided to give the choice to the user to observe if one method dominates over the other or not.

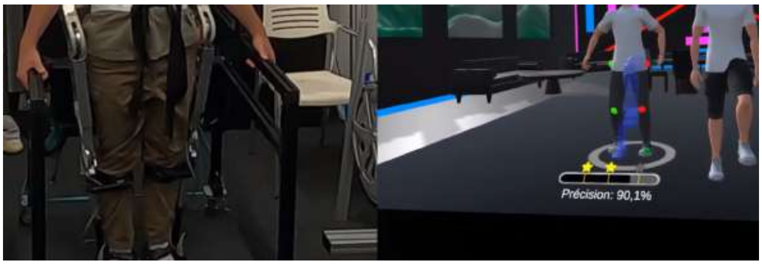


(a) Image of the mirrored visual feedback.

(b) Image of the anatomical visual feedback.

Figure 3.13: On the left, the visual feedback is mirrored, with the player raising their right leg while the instructor and the mirror-represented avatar raise their left legs. On the right, the visual feedback is anatomical, as the user, the instructor, and the avatar representing the user lift the left leg.

The game's development was focused on the lower limbs, with only positions involving leg movements being implemented. The data used to determine whether a position is valid or not includes the angles of the knees, hips, and the abduction angle of each leg. An error margin was incorporated to allow for less strict positioning requirements and account for errors that may arise from imperfect calibration of the exoskeleton on the patient. To add difficulty, various levels of difficulty were introduced, reducing the error margin and increasing the number of different positions to be performed as the difficulty level rises. To assist users in identifying which part of their body is not correctly positioned, spheres were placed on the avatar's knees and hips. These spheres turn green when the positioning is correct and red when it is not (see Figure 3.14).



(a) The position is not correct, so the indicators for the incorrectly positioned leg are in red

(b) Position is correct, so all indicators are green

Figure 3.14: Each indicator turns red when the angle requested is not the right one (top image) and turns green once the correct position has been achieved (bottom image).

As the study's main objective was to test the system's feasibility and usability, only six different positions were developed, and the variation in difficulty levels is limited to three due to the limited number of possible positions.

3.5 Rehabilitation video game

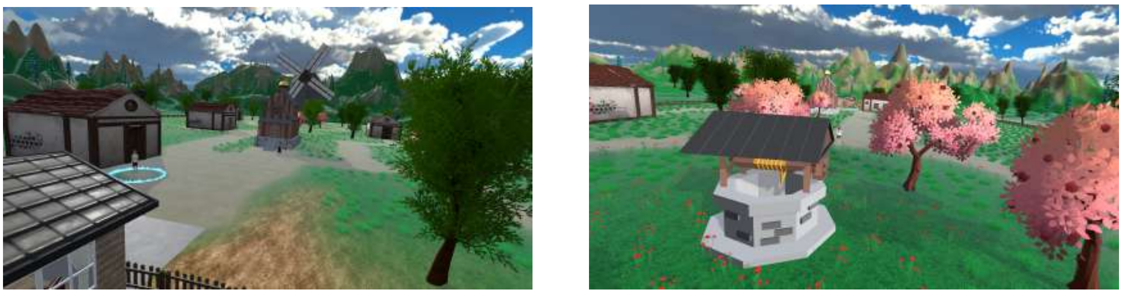
The exergame described above is a repetitive one, commonly used for rehabilitation purposes. However, the repetitiveness of such exercises lacks motivational appeal, resulting in users becoming quickly bored. This aspect poses a significant challenge for home-based rehabilitation because patients must motivate themselves to perform the exercises, and the lack of excitement and motivation hinders their long-term commitment. To address this issue, the rehabilitation video game described below was developed.

The game was designed and created to minimize the exercise and rehabilitation aspects typically found in exergames and instead, closely resemble a traditional video game. It combines game design elements, storytelling, various mini-games, and exploration of a virtual world. The storyline, diverse mini-games, and means to move within the game are described in the following sections.

3.5.1 Story-line

The storyline was chosen to create a game lasting between 20 and 30 minutes, allowing testers to complete the game if they have the desire and motivation, or stop halfway if they prefer. The scenario unfolds in a small village called WalkiTown, where the sacred gem of the village has been recently stolen. The player takes on the role of an investigator summoned to recover the gem and apprehend the thief. To accomplish this, the player must explore the village and interact with its inhabitants to gather information. However, the information won't be freely given; the player must defeat each villager in a game to obtain the desired information.

To provide the player with a sense of freedom while guiding them through the game, a world has been crafted (see Figure 3.15). This world is designed to offer an illusion of freedom while incorporating various aspects of game design to guide the player. The different stages or objectives are placed strategically, so the player doesn't have to backtrack, considering that one of the movement modes does not allow backward movement, as explained in section 3.5.3.



(a) (b)

Figure 3.15: The game takes place in a lush, green village surrounded by mountains. As the player embarks on their adventure, they explore the village, interacting with various villagers along the way.

The game progresses primarily through a series of rehabilitation mini-games, including the main exergame described in section 3.5. Other games have been developed to introduce diversity and incorporate cognitive challenges, and they are described in the following sections.

3.5.2 Side games

Indeed, these games were specifically developed to offer a distinct experience from the main exergame while still maintaining a rehabilitative aspect. The goal was to introduce a wide range of activities, ensuring a diverse and engaging game-play experience for the players. Each game was carefully designed to target various aspects of rehabilitation, such as motor skills, balance, coordination, and cognitive abilities, adding both fun and therapeutic value to the overall gaming experience. By incorporating different mechanics and challenges, the players are encouraged to explore new interactions and stay motivated throughout their rehabilitation journey.

3.5.2.1 BeatHands game

The first game, called BeatHands, draws inspiration from the game Beat Saber used in rehabilitation studies [25, 26]. This game primarily focuses on upper-body movements while also requiring the player to work on their balance. The objective of the game is to touch targets, using the right hand for blue targets and the left hand for red targets (see Figure 3.16). The player has one minute to touch as many targets as possible, as a new target appears as soon as the previous one is successfully hit. Using hand-tracking technology, the player can play without the need for controllers, allowing for a more immersive and hands-free experience. Additionally, BeatHands offers three different difficulty levels, introducing targets placed at increasingly distant distances to increase the challenge for players.

By incorporating upper-body movements and balance exercises, BeatHands provides an engaging and beneficial experience, complementing the rehabilitation efforts targeted by the main exergame.

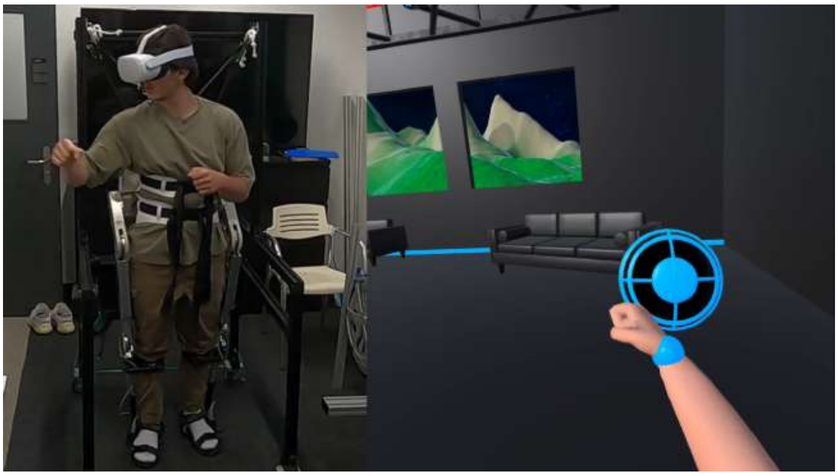


Figure 3.16: The player is in the process of reaching out with their right hand to touch the blue target and earn a point. Once the target is touched, a new target will appear elsewhere for the player to aim at.

3.5.2.2 Balance game

This game is based on a 2D rehabilitation game that was created for the same exoskeleton before this study (see Figure 3.17).

Figure 3.17: The "Lava game," which served as the inspiration for the balance game in this study, requires the player to control a white ball inside a square by leaning in the desired direction to prevent it from leaving the boundaries.

The objective of the game is to move a green ball to different numbered points in ascending order. To move the green ball, the user must shift their weight in the desired direction by leaning (see Figure 3.18). The sole sensors are utilized to determine the user's weight distribution, and the center of mass for all cells is calculated to determine the direction in which to move the ball. This system allows for simple and precise control of the ball by the user. The speed of the ball remains constant and is not affected by the force exerted by the user. Different difficulty levels are also available for this game, with higher difficulties increasing the speed of the ball.

Figure 3.18: Image of the balance game in which the player moves a green ball towards the numbered points by leaning in the desired direction.

3.5.2.3 Shifumi game

This game was developed as a bonus game for those who manage to reach the end of the story. The game is a classic "shifumi" (rock, paper, scissors) following the standard rules: Rock beats scissors, paper beats rock, and scissors beat paper. The player simply needs to form the desired shape with their hand, and thanks to the hand tracking system, the game recognizes the intended shape using the position of the phalanges of each finger (see Figure 3.19). The player competes against an in-game avatar that plays randomly all the time, and the first to reach 3 points wins.

Figure 3.19: Image of the bonus game: shifumi ("rock, paper, scissors"). The player wins by making a leaf while his opponent makes a rock.

This game was developed to add a purely recreational aspect, in order to observe users' reactions to a game that initially has no rehabilitation aspects.

With the story, the world, and the different games having been described, the only thing left is the tool that allows the player to move freely in the world, as described in the following section.

3.5.3 Walking in place

Allowing the user to navigate in a virtual world serves two objectives. Firstly, it aims to approach what a traditional video game can offer in terms of freedom. Secondly, it adds an aspect of walking since the targeted rehabilitation in this study focuses on gait rehabilitation. Currently, virtual reality enables users to move freely in the real world, thereby moving their avatar in the virtual world. However, this system is not usable in this study because one of the objectives is the possibility of rehabilitation at home, where there may not be sufficient space for free movement. Thus, static walking was chosen to enable virtual movement while remaining static in the real world.

Some studies have already explored walking in place in VR [27, 28, 29], and certain aspects of the three walking modes developed in this study were inspired by previous research. However, these studies consider the possibility of turning oneself to rotate in the virtual world, which was not the case in this study for several reasons. First, the system includes the use of a safety frame with a body weight support, as described in section 3.6.3, which is fixed during the test. Second, to make the avatar turn in the game, it would be necessary to determine if the user is rotating their entire body and not just their head, which would theoretically be possible with the IMU located at the back of the exoskeleton. However, the time allocated to this study was insufficient to develop this system, making it a potential point of improvement for the future. Another reason is that rotating oneself in VR could quickly lead to a feeling of imbalance, which is not desirable for patients, though this aspect needs testing to be confirmed.

The question of rotation, therefore, becomes a crucial point in the development of walking in place for this system. Hence, two different ways of turning were developed and tested. But before addressing this question, another interesting point is how to translate the player's movements in the real world to movement in the virtual world. The choices made regarding this issue will be further explained.

The simplest and most commonly used solution in studies on walking in place is linear displacement, which means moving the camera at a constant speed when the user walks. However, this method was not chosen for one specific reason: it is not easy to determine when a person is walking or not and, consequently, when to start and stop the movement. If we consider that a person is walking when one of their feet is off the ground, the user could cheat by leaving one leg off the ground to move, for example. To avoid this, one could wait for two steps before starting the movement to ensure that the user is indeed walking. However, this would make the walking movement unrealistic and unpleasant since it would be out of sync with the real movement. An initial attempt to address this issue involved using teleportation, which is often used in VR to avoid cybersickness that can be caused by in-game movements. The attempt using teleportation was to teleport the user a short distance each time a walking checkpoint was reached. The walking checkpoints were set at three locations: slightly raised foot during an incline, raised foot, and slightly raised foot during a decline. However, this technique was not retained because having so many teleportations was particularly uncomfortable and caused more cybersickness than constant movement even with a phase shift. Therefore, it was decided to avoid teleportations for movement, and a different system was developed, which resolved the aforementioned issues and allowed the avatar to move faithfully according to the user's movements.

The method used is to calculate the difference in height of the lifted foot between two game frames and move the avatar by that distance multiplied by a constant velocity factor for each frame. This technique allows for a movement that faithfully reflects the user's movements and avoids the jarring effect of teleportation. Nonetheless, the possibility of experiencing cybersickness with this movement method still exists. Therefore, an anti-cybersickness method was developed based on the same principle. When the user walks, it is not their avatar that moves but rather a marker placed on the ground, towards which the user can teleport by gazing at it for more than one second (see Figure 3.20).

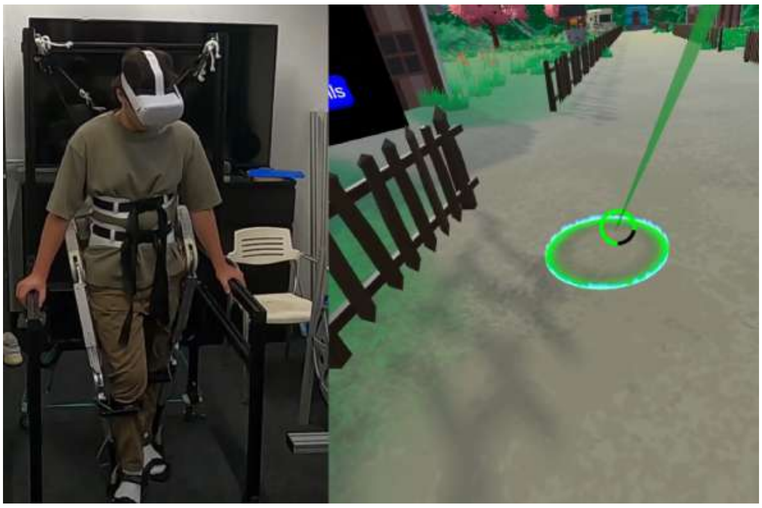


Figure 3.20: Image of the anti-cybersickness mode for walking. The user moves a marker and can teleport to it by looking at it for 1 second.

Once the walking methods were developed and validated, it was necessary to find a way for the user to turn and navigate freely in the virtual world, considering the limitations mentioned earlier. Therefore, two different methods were implemented for testing. The first method, based on teleportation, allows the user to choose the direction in which to move with each step. Each time a foot lift is detected using the force cells in the soles, the avatar is instantly turned (teleported) in the direction the user is looking at that moment. The stepping movement is then made in that direction until the next foot lift. This technique requires the user to look in the desired direction and immediately afterward look forward to avoid turning again during the next step. The second method simply moves the avatar in the direction the user is looking at. This method is simpler and avoids teleportations to rotate, but it does not allow going backward, or it is very difficult since it requires the user to look behind them. This limitation is the main reason why the virtual world is designed in a way that requires always moving forward and never backward. Both of these methods for turning have their limitations, and further research is needed to obtain a more enjoyable and realistic system in this regard.

The three walking modes are as follows:

- Mode 1:
  The walking method is based on moving the avatar according to the movement of the stepping foot, and the rotation method involves rotating the avatar in the direction the user is looking at every step.
- Mode 2
  The walking method is the same as in Mode 1, and the rotation method involves moving the avatar in the direction the user is looking at.
- Mode 3
  The walking method uses the anti-cybersickness technique, moving the avatar only by teleportation toward a marker that is moved in the same manner as in Mode 2.

Once the entire system was fully implemented, pilot tests were conducted to gather information and results on the feasibility and usability of the system. The next section discusses the setup of these tests.

3.6 Pilot test

Pilot tests were conducted to gather information and results on the feasibility and overall usability of the rehabilitation system at home, as well as to address various decisions made during its development.

3.6.1 Test protocol

The test protocol was designed to address different questions and assess the general feasibility and usability of the system. The questions that this study aimed to answer are as follows:

- Question 1:
  What is the best static walking mode (i.e. section 3.5.3), is it well tolerated, and does it induce cybersickness?
- Question 2
  Which interaction style with the virtual environment (i.e. section 3.3) is more intuitive and preferred: using controllers or a laser pointer?
- Question 3
  What is the impact on motivation and engagement with the rehabilitation video game (i.e. section 3.5) compared to repetitive exergames (i.e. section 3.4) alone?
- Question 4
  Is the system, including virtual reality, the exoskeleton, and the safety frame (i.e. section 3.6.3), comfortable and enjoyable to use?

Two slightly different test protocols were created to avoid biases concerning the interaction style with the virtual environment and the walking modes. Participants were randomly assigned to one of the two groups. The protocols were divided into three distinct parts: the first part involved filling out a pre-test questionnaire. The second part was the testing phase itself, and the third part involved filling out a post-test questionnaire. The pre-test questionnaire mainly consisted of the Simulator Sickness Questionnaire (SSQ) [30, 31], which was used to assess if the system induced any cybersickness in the users. The test was then conducted before the participants completed the post-test questionnaire, which also included the SSQ to evaluate any differences in the users' conditions between the beginning and the end of the test. The rest of the questionnaire included questions on different aspects of the system to address the questions mentioned earlier. The detailed protocol followed during the testing phase is available in Appendix A.2.

3.6.2 Test participants

As this was a pilot study, only healthy people took part in the tests. Two types of participants were selected to take part in these tests. The first type of participants were members of the start-up Autonomyo, and the second type consisted of physiotherapists from different Swiss establishments. In total, 3 physiotherapists and 7 members of Autonomyo participated in the tests. Development tests were conducted before the testing phase to adjust, refine, and debug the system, and some members also took part in these tests. This could potentially introduce bias to the results. However, these users were instructed to provide the same feedback they had previously given during the development tests and to react as if it were their first test to minimize any potential bias.

By involving both members of the start-up and external physiotherapists, the pilot tests aimed to gather diverse perspectives and feedback to assess the system's comfort, and usability from different user groups. The insights and suggestions from both groups were valuable for improving the system and addressing any issues or concerns that emerged during the testing phase.

3.6.3 Safety frame

During the development phase, crutches were initially used as a means of providing stability and safety to the users. However, crutches proved to be less than ideal for this system for several reasons. Firstly, they required the use of hands, making it difficult to use them while playing certain games like BeatHands where hands are essential. Secondly, the balance and stability provided by crutches were not optimal and demanded considerable effort from the user.

For the testing phase, the crutches were replaced by a safety frame (see Figure 3.21) for the reasons mentioned above. The safety frame consists of a frame that users can hold when needed and a back support system with elastic bands that can restrain the user and prevent them from falling in case of balance loss. The safety frame offers significantly greater security compared to crutches and provides enhanced comfort as hands are not constantly occupied, and the effort required to maintain balance is reduced compared to using crutches.

Figure 3.21: Image of the safety frame used for the test session.

(a) The setup used during the development phase

(b) The setup used during the pilot test phase

Figure 3.22: The setup includes the VR headset, the exoskeleton, and either crutches or the safety frame. The setup with the safety frame provides better support and safety for the user, who is supported by the elastic system and can hold onto the parallel bars while keeping their hands free.

The next section presents and discusses the results obtained during the pilot tests.

Chapter 4

Results

The results obtained from the pilot test with 10 participants will be presented in this chapter. First, the SSQ results will be presented and analyzed, followed by an exploration of the usability issues discussed in Section 3.6.1. These findings will be further discussed in the final section of this chapter.

4.1 Cybersickness

Prior to presenting and analyzing the results, it is crucial to grasp the functioning of the Simulation Sickness Questionnaire (SSQ). Originally developed for military flight simulators, this questionnaire is now commonly employed to quantify cybersickness induced by virtual reality. The SSQ consists of 16 questions addressing diverse symptoms, categorized into three groups: nausea, oculomotor disturbance, and disorientation. Each of the 16 questions offers four potential responses indicating the severity of symptoms: none (0), slight (1), moderate (2), and severe (3). The total score is calculated by using specific formulas that assess the scores for nausea, oculomotor disturbance, and disorientation, ultimately yielding the overall score. The breakdown of symptoms by category, along with the formulas for calculating the various scores, is presented in Figure 4.1.

SSQ Symptom	Weight N	O	D
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total	[1]	[2]	[3]

$$N = [1] \times 9.54$$
$$O = [2] \times 7.58$$
$$D = [3] \times 13.92$$
$$TS = ([1] + [2] + [3]) \times 3.74$$

Figure 4.1: This image is taken from the study conducted by Bimberg et al. [31] and depicts the symptom distribution categorized, along with the formulas necessary to compute the different scores within each category, which collectively contribute to the calculation of the overall score.

The total score was used to categorize the severity of experienced symptoms, facilitating the quantification of simulator sickness caused by the tested simulator. The categorization based on the score used initially is detailed below (see Figure 4.2). This categorization assumes that the participant's pre-test score is 0, which is not realistic and depends on various factors such as the weather, time of day, or the participant's mood, as evidenced by the results obtained. This categorization has thus been widely criticized [31, 32], particularly in the context of cybersickness in virtual reality, as achieving a score higher than 20 is relatively easy and may not necessarily reflect a state of illness. For these reasons, this study will refrain from using a specific categorization. Instead, an approach involving the analysis of the difference between the total scores before and after the test will be employed. User comments will also be considered, as they, along with the various scores, will provide insights into the system's impact in terms of cybersickness. This approach will enable us to draw conclusions about the system's feasibility and usability.

SSQ Score	Categorisation
0	No symptoms
<5	Negligible symptoms
5–10	Minimal symptoms
10–15	Significant symptoms
15–20	Symptoms are a concern
>20	A bad intervention

Figure 4.2: This image depicts the categorization of symptom severity based on the total score.

Therefore, the SSQ was completed twice for each participant: once before the test to determine their initial condition, and once again after the test to assess their condition post-test, enabling a comparison with their state before the test. A summary of the main results is provided below (see Figure 4.3), while the comprehensive results are available in Appendix B.1.

	Participant 1	Participant 2	Participant 3	Participant 4	Participant 5	Participant 6	Participant 7	Participant 8	Participant 9	Participant 10
Weighted nausea score (N) (Pre-test)	9,54	0	9,54	9,54	0	0	9,54	19,08	0	19,08
Weighted Oculomotor score (O) (Pre-test)	0	15,16	7,58	30,32	15,16	0	15,16	22,74	15,16	7,58
Weighted disorientation score (D) (Pre-test)	0	0	13,92	13,92	0	0	13,92	27,84	0	0
Total SS Score (Pre-test)	**3,74**	**7,48**	**11,22**	**22,44**	**7,48**	**0**	**14,96**	**26,18**	**7,48**	**11,22**
Weighted nausea score (N) (Post-test)	28,62	19,08	19,08	28,62	47,7	0	19,08	28,62	19,08	85,86
Weighted Oculomotor score (O) (Post-test)	30,32	22,74	37,9	60,64	60,64	15,16	15,16	15,16	22,74	83,38
Weighted disorientation score (D) (Post-test)	13,92	0	69,6	83,52	13,92	13,92	13,92	0	41,76	83,52
Total SS Score (Post-test)	**29,92**	**18,7**	**44,88**	**63,58**	**52,36**	**11,22**	**18,7**	**18,7**	**29,92**	**97,24**

Figure 4.3: This image summarizes the SSQ questionnaire results before and after the test conducted with 10 participants. It displays only the scores for nausea, oculomotor, disorientation, and the total Simulator Sickness (SS) score. For a comprehensive set of results, please refer to Appendix B.1.

To begin with, it's worth noting that the pre-test total score is greater than 0 for nearly all participants, with an average of 11.22 ± 7.66. This average score would already fall into the range of significant symptoms according to the aforementioned categorization. The three most commonly reported symptoms before the commencement of the test are fatigue, eye strain, and sweating. Given that the tests were conducted during the midsummer period, within a non-air-conditioned environment, and often in the late afternoon, these symptoms are both logical and anticipated. It's crucial to take these factors into account when interpreting the post-test results. The average total score stands at 38.52 ± 25.26, which is not particularly high as noted in the study by Brown et al.[32]. However, the standard deviation is notably large, indicating significant variability in the results. This broad range can be attributed to the fact that VR is a unique tool that doesn't evoke the same response in everyone. Some individuals exhibit minimal or no symptoms in response to VR, while others experience discomfort or sickness rapidly. For instance, Participant 10 mentioned that they disliked having something on their face and experienced discomfort after briefly trying the VR headset for 30 seconds before the test. Similar comments were made by Participant 4, which elucidates the higher post-test total scores for these participants. While other participants may not necessarily report feeling unwell, certain symptoms such as fatigue, eye strain, and sweating increased significantly. Additional symptoms like headache, general discomfort, a sensation of head heaviness, and blurred vision also emerged.

The increase in the oculomotor score was anticipated, as symptoms like fatigue, eye strain, difficulty focusing, and momentarily blurred vision are known and commonplace after VR usage. The nausea score also saw a noticeable uptick, primarily attributed to increased sweating and general discomfort, rather than symptoms like actual nausea, heightened salivation, or stomach awareness. These latter symptoms typically signify a more intense state of discomfort than simply increased sweating. The elevation in sweating and general discomfort can be linked to the fact that using the exoskeleton can be physically taxing and wearing it might not be particularly comfortable, as will be explored in the following section. The disorientation score exhibited a substantial increase among individuals highly susceptible to negative VR effects, but the rise was less pronounced in those with lower or no sensitivity to cybersickness.

Following these observations, it becomes crucial to acknowledge that virtual reality is subject to individual variability, and the experienced symptoms are contingent upon an individual's sensitivity to cybersickness. To validate these observations, the disparity between participants' states before and after the test was calculated and is depicted in Figure 4.4 below.

Participant	Total score difference
1	26,18
2	11,22
3	33,66
4	41,14
5	44,88
6	11,22
7	3,74
8	-7,48
9	22,44
10	86,02
Mean	27,3
Median	24,31
Standard Dev.	25,09

Figure 4.4: This image showcases the disparity between the pre-test and post-test total scores for all participants, as well as the mean, median, and standard deviation values.

The average of these differences is 27.3, but the most significant aspect is the large standard deviation of 25.09. Remarkably, three values (participants 4, 5, and 10) are notably higher (> 40), and two of these three participants clearly expressed discomfort and a sense of illness after the test. Conversely, four values are notably lower (< 15), signifying that these participants didn't experience cybersickness during the test. The conclusion drawn from these results suggests that virtual reality may not be universally suitable for all patients, as the symptoms experienced by individuals sensitive to cybersickness are undesirable within a rehabilitation context.

4.2 Usability

Usability was evaluated through a combination of different questions and an analysis of participants' reactions and feedback throughout and after the test. An overview of the questionnaire results is provided in Figure 4.5 below.

Questions / Results	Participant 1 (A)	Participant 2 (B)	Participant 3 (A)	Participant 4 (B)	Participant 5 (A)	Participant 6 (B)	Participant 7 (A)	Participant 8 (B)	Participant 9 (B)	Participant 10 (A)	**Average or percentage**
Has already done VR	Yes, 2-3 times	Yes, 2-3 times	Yes, 2-3 times	Yes, 2-3 times	Yes, 2-3 times	No	Yes, 2-3 times	Yes, 2-3 times	Yes, 2-3 times	No	Yes, used to it: **0%** Yes, 2-3 times: **80%** No: **20%**
Took part in development tests	No	No	No	No	Yes (All)	No	Yes (Dance game only)	Yes (All)	Yes (All)	No	Yes: **40%** No: **60%**
Preferred without controller	5	3	5	2	3	5	5	5	5	5	4,3
The pointer was pleasant and intuitive	5	3	4	2	4	5	5	4	4	5	4,1
Preferred walking mode	Mode 2	Mode 1	Mode 1	Mode 2	Mode 2	Mode 2	Mode 2	Mode 2	Mode 2	Mode 2	Mode 1: **20%** Mode 2: **80%**
The game can increase patient motivation and commitment over time, compared with repetitive exergame.	4	4	5	4	4	4	4	5	5	4	4,3
the exoskeleton was comfortable and pleasant to use.	1	2	3	4	4	4	3	4	3	2	3
the VR system was comfortable and pleasant to use.	4	4	4	2	3	4	4	4	4	1	3,4
the safety frame was comfortable and pleasant to use.	5	5	4	4	4	4	4	5	4	5	4,4
the entire system (exoskeleton, VR system and safety frame) is comfortable and pleasant to use.	4	3	4	3	4	4	4	4	4	2	3,6

Figure 4.5: This image summarizes the responses of the 10 participants to the different questions in the pre and post-test questionnaires. Responses containing numerical values were assigned the following scale: strongly agree (5), agree (4), neither agree nor disagree (3), disagree (2), and strongly disagree (1). The full list of questions presented to the participants is available in Appendix A.2.

To begin, none of the participants were familiar with VR, and the majority had only limited prior exposure to it. Various factors could explain this result, including the cost of VR systems and the relatively recent introduction of this technology to the market, resulting in its limited general use. Four participants had been involved in the system's developmental testing. To mitigate potential bias in the results, these participants were requested to offer feedback consistent with their previous input during the development tests and to respond without taking into account any prior testing they had participated in.

Addressing the second question posed in Section 3.6.1, users were required to navigate the menu during the test, utilizing controllers or a laser pointer following a predefined sequence based on their assigned group. The system was developed with the intention of providing users with hands-free mobility for balance and a greater sense of freedom. As a result, participants were asked whether they preferred hands-free interaction without controllers or if they felt more comfortable using controllers. The consensus was nearly unanimous, with participants expressing a preference for hands-free interaction. The reasons cited included the cumbersome nature of controllers and the challenge of using them effectively. Physiotherapists also overwhelmingly supported the hands-free approach, considering it more suitable for patients. Participant 4, who favored using controllers, noted that the tactile feedback from buttons enhanced their sense of immersion in the virtual environment. Subsequently, participants' opinions on using the laser pointer to interact with the application interface were highly positive and aligned with the previous question's findings. The intuitive and user-friendly nature of the pointer system was underscored. However, it was mentioned multiple times that this method requires users to avoid looking at buttons to prevent unintended presses. Suggestions for improvement encompassed the implementation of double confirmation and slightly extending the required button press time.

The following question delved into static walking, specifically exploring participants' preferences between the two developed walking modes. Initially, the second walking mode was favored over the first due to its perceived intuitiveness. Participants found the small teleportations used in the first mode for turning less enjoyable and potentially more disorienting than in the second mode. Interestingly, during the tests, the walking mode was changed midway without notifying participants, and only half of them noticed the difference until it was explicitly explained. The opinions of physiotherapists on static walking were not unanimous. While two out of three therapists recognized the therapeutic value and considered it the best option within the constraint of remaining stationary, the third therapist found the method neither intuitive nor functional. A large majority (> 70%) of participants viewed the ability to navigate within a virtual world as a positive and enjoyable aspect.

The subsequent question posed to participants was: Can such a rehabilitation video game increase patient motivation and engagement over time compared to repetitive exergames? The response was unanimous in recognizing the benefits of incorporating multiple diverse games that extend beyond pure exercises. The curiosity to explore forthcoming exercises and game progression was deemed effective in boosting engagement and motivation.

Subsequent questions centered on the comfort and appeal of various tools employed in this study's system. Comfort while wearing the exoskeleton yielded mixed results, with feedback indicating that it is not particularly comfortable but also not extremely uncomfortable. This outcome was expected, given that the exoskeleton is still in development and the transparent mode, while providing no specific support other than carrying its own weight, introduces unexpected and undesired movements that impact comfort. Participants with low or no sensitivity to cybersickness generally found the virtual reality system pleasant, whereas it was particularly discomforting for those who were sensitive to it. The safety frame was generally well-received and appeared necessary for optimal system use. A suggestion was made to render the safety frame bars visible in the virtual world to prevent inadvertent collisions. The overall comfort of the system, as a whole, was consistent with earlier results and seemed to be accepted by users despite its imperfections and potential for improvement.

4.3 Discussion

With the results now presented, it is possible to discuss them and attempt to address the questions posed in Section 3.6.1.

4.3.1 Walking mode

Question 1: what is the best static walking mode, is it well tolerated, and does it induce cybersickness?

As evidenced by the results, the second walking mode was preferred over the first due to its greater intuitiveness and the absence of teleportation for turning. Static walking was well-tolerated by participants who were not highly sensitive to cybersickness. However, participants 4 and 10 did not tolerate either mode well, prompting the testing of the third mode created specifically for sensitive individuals. Participant 4 favored this mode over the others, yet it failed to provide an enjoyable experience due to the required teleportation for movement. Participant 10, on the other hand, did not strongly prefer this mode and it did not notably improve their comfort in VR. Among the remaining eight participants, opinions on this mode were mixed, with most recognizing its potential benefits for individuals susceptible to cybersickness. These findings suggest that virtual reality should be selectively used, targeting individuals who exhibit interest, curiosity, and minimal sensitivity to cybersickness. With the second static walking mode being the most well-received, future efforts should concentrate on refining this mode to address remaining issues, such as the inability to move backward. Teleportation, whether for advancing or turning, appears to be a less effective method of locomotion compared to smooth movement, and it doesn't seem to exacerbate cybersickness since the user's body movements remain coherent with virtual world displacement. The application of static walking as a means to navigate within a virtual environment had not been implemented, or at least not to our knowledge, for the purpose of gait rehabilitation. The principal reason for this lies in the fact that prior research on this subject primarily employed apparatuses like treadmills to enable walking without requiring a static walking setup. Therefore, the use of static walking for home-based rehabilitation offers a promising avenue to facilitate movement in the virtual realm without relying on external equipment. Nonetheless, additional research is needed to ascertain the most suitable form of static walking system to achieve this objective.

4.3.2 Interface interaction

Question 2: which interaction style with the virtual environment is more intuitive and preferred: using controllers or a laser pointer?

The pointer system developed in this study appears to be remarkably intuitive and effective, garnering a strong preference over controllers among users. While the laser pointer interaction has been well-received, there is potential for further refinement to enhance its comfort and usability. Considering the positive reception and user satisfaction, it is advisable to retain and continue refining this method for interacting with the virtual interface in future endeavors and research involving this system. An interaction method like this is quite uncommon in studies that have developed rehabilitation games, with the predominant approach being the use of controllers to interact with the interface. Given the results, it's likely that systems like this could replace the use of controllers in the coming years.

4.3.3 Motivation and engagement

Question 3: What is the impact on motivation and engagement with the rehabilitation video game compared to repetitive exergames alone?

The findings in this context point towards a tangible interest in the development of rehabilitation games that depart from repetitive structures, resembling more closely the design principles of the mainstream video game industry while effectively integrating essential rehabilitation components. Gamification is gaining prominence within rehabilitation research, but currently, it appears to yield inadequate motivational and engagement benefits over extended periods, regardless of whether it's implemented in clinical environments or home settings. Further comprehensive testing is required to validate the apparent insights presented in this study.

4.3.4 System comfort

Question 4: is the system, including virtual reality, the exoskeleton, and the safety frame, comfortable and enjoyable to use?

The results primarily confirm the importance of the safety frame, which offers essential support to prevent patient falls, along with the parallel bars providing stable points of contact. Physiotherapists have underscored the practicality and significance of the safety frame for patients. While the VR system offers a reasonable level of comfort for patients, its use should be limited to those who are interested, curious, and do not exhibit cybersickness sensitivity. As anticipated, the exoskeleton did not deliver sufficient comfort to users, but the discomfort factors outlined earlier are expected to be addressed upon the completion of the exoskeleton's development.

4.3.5 Games

In addition to these findings, the various games developed for the rehabilitation video game have generated considerable interest among physiotherapists. They have found these games enjoyable, beneficial for patients, and appreciated the diversity of movements they offer. However, there were observations that some movements could be further refined to closely align with those required for effective rehabilitation. This consideration holds significant importance for future work, as these games need to undergo modifications in collaboration with physiotherapists to ensure genuine medical relevance.

4.3.6 Mirrored VS anatomical feedback

The substantial majority of participants (9 out of 10) expressed a preference for mirrored feedback rather than anatomical feedback. The participant favoring anatomical feedback highlighted that the setup resembles a gym class scenario with an instructor to imitate. When the instructor asks everyone to lift their right leg, they all instinctively comprehend to lift their right leg. For the remaining 9 participants, mirrored feedback appeared the most intuitive. This outcome aligns with general trends observed in video games, such as Just Dance, where players are required to mimic a mirrored avatar's movements. However, another approach used in studies, as exemplified in the study by Hamzeheinejad et al. [9], involves positioning the feedback-providing avatar to face the same direction as the participant (thus showing the avatar's back), in which case anatomical movement in relation to the avatar becomes the more intuitive choice.

4.3.7 Virtual reality VS 2D screen

An open-ended question was included at the end of the post-test questionnaire to capture participants' favorable and unfavorable perspectives regarding the use of VR in rehabilitation compared to performing similar activities on a traditional screen. Here is a compilation of the positive and negative aspects that emerged from their responses.

- Positive points
  - Better immersion with VR headset.
  - Can help motivate people to do something they don't want to do in the first place.
  - Can help to obtain better quality measurements easily.
  - A break from the hospital environment.
  - Some games, like BeatHands, make more sense in VR.

- For static walking, visual feedback gives a more realistic sense of movement than on a 2D screen.

- Negative points
  - Majority of people are not used to it, can be complicated to accept.
  - Increased physical and visual fatigue.
  - Potential cybersickness.
  - Set-up is more time-consuming and cumbersome than on a 2D screen.
  - Technology not yet fully mature (visual quality and comfort).

The feedback gathered from these responses indicates that VR technology may still be considered relatively new, and individuals might not be sufficiently accustomed to these systems to readily implement them in rehabilitation settings. Nonetheless, considering the swift progress of this technology, it's increasing everyday use could mitigate the influence of negative factors, ultimately enabling its effective integration into rehabilitation and leveraging the mentioned positive aspects.

Chapter 5

Conclusion

The Autonomyo VR rehabilitation system presented in this study encompasses several components: the Autonomyo exoskeleton, a safety frame providing user support, and a VR rehabilitation application developed as part of this work. The application was designed with the goal of achieving a user-friendly, "plug-and-play" home rehabilitation system. A rehabilitation game was created to resemble a conventional video game while retaining rehabilitation aspects, aimed at enhancing patient enjoyment, motivation, and engagement over the medium to long term. A "walking in place" system was devised to enable users to freely navigate within a virtual world, complemented by a variety of games merging cognitive, rehabilitation, and game design elements to guide users through a gaming adventure. The application also includes a complete body avatar developed using exclusively the information transmitted by the exoskeleton to achieve simplicity of use while ensuring precise movement tracking.

The primary objective of this paper was to test the feasibility and usability of the overall system. A secondary goal was to evaluate various design choices within the rehabilitation game, encompassing static walking, interface interaction methods, and rehabilitation mini-games, with the aim of establishing best practices for the future development of similar applications. To address these objectives, a testing session involving 10 participants, including 3 physiotherapists and 7 Autonomyo team members, was conducted. Key findings indicate that a rehabilitation game, in contrast to a repetitive exergame, could potentially enhance motivation, engagement, pleasure, and fun for patients during rehabilitation sessions. The system's comfort was deemed acceptable yet improvable, primarily by opting for exoskeleton modes that provide better support and assistance rather than using the transparent mode. The potential for cybersickness was also assessed using the Simulator Sickness Questionnaire (SSQ), revealing that VR for rehabilitation purposes should be reserved for individuals who are interested and not susceptible to cybersickness. For those who are less sensitive or not affected, displacement movements do not pose a problem, as their actions correlate coherently with virtual world navigation.

Guidelines learned from the conducted tests include, among others, avoiding the use of controllers to allow patients to have the hands-free capability for holding onto the safety frame and avoiding any type of teleportation during movement to prevent disorientation or potential cybersickness.

Despite the positive aspects introduced by the system, certain aspects need improvement and further exploration in future work to achieve sufficient usability for rehabilitation. The developed second static walking mode is a promising starting point but necessitates further refinement to enhance its intuitiveness and resemblance to real walking. The complete body avatar tracks simple movements effectively but may become imprecise during certain motions due to variables such as user height or weight. Enhancements must be implemented while preserving the "plug-and-play" nature of the system. As per the physiotherapists' feedback, the rehabilitation mini-games provide a solid foundation but require collaboration with specialists to ensure patients execute appropriate movements. An essential enhancement required to provide physiotherapists with the complete feedback necessary for a productive rehabilitation session involves enabling them to observe the proceedings inside the VR headset on an external screen. Presently, this capability is lacking due to the limitation that the exoskeleton's Wi-Fi does not support an internet connection, preventing the real-time sharing of the VR headset's content. Beyond these areas for improvement, VR technology is relatively new and under active development, with most individuals not yet accustomed to it and the quality and comfort of VR headsets still limited. It is likely that more advanced VR systems will emerge in the coming years, potentially significantly enhancing a system like the one presented in this study.

In conclusion, the Autonomyo VR rehabilitation system appears to be feasible for home-based rehabilitation, and the rehabilitation game holds promise for increasing motivation and engagement. However, improvements are still necessary to achieve a level of usability suitable for rehabilitation purposes.

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Appendix A

Pilot test protocol

A.1 Test plan

A.1.1 Document overview

This document describes the test plan used for conducting the pilot test during the development of the virtual reality (VR) rehabilitation system. The goals of this pilot testing include assessing the feasibility and usability of the system as a whole and evaluating different parameters to obtain the most satisfactory version for the user.

The pilot test objectives are:

- To determine design inconsistencies and usability problem areas within the user interface and content areas.
- Exercise the application under controlled test conditions. The data will be used to assess whether feasibility and usability objectives for the system as a whole have been achieved.
- To compare different usability parameters to achieve maximum user satisfaction without compromising system efficiency and effectiveness.
- To evaluate the impact on motivation between a conventional rehabilitation game versus a video game including different rehabilitation exercises as well as cognitive games.

Two user groups are created among the participants. Each group has the same tasks to perform but in a different order. The number of participants per group is 5.

A.1.2 Methodology

A.1.2.1 Participants

Two participant groups were recruited: Autonomyo members and physiotherapists. Some Autonomyo members had prior exposure to certain tasks as a result of their involvement in developmental testing. On the other hand, the physiotherapists had no previous acquaintance with the tasks but brought medical knowledge related to the subject into the study. The number of participants is 10. The participants' responsibilities will be to attempt to complete a set of representative task scenarios and to provide feedback regarding the usability and acceptability of the system. The participants will be directed to provide honest opinions regarding the usability of the system and to participate in post-session subjective questionnaires and debriefing.

A.1.2.2 Training

The participants will receive an overview of the usability test procedure, equipment, and software. They will first be trained to familiarize themselves with the exoskeleton after it has been calibrated. They will then be trained to familiarize themselves with virtual reality.

A.1.2.3 Procedure

Participants will take part in the pilot test at Autonomyo's site in Ecublens (Switzerland). An Oculus Quest 2 VR headset with the application will be used while being in the exoskeleton. The participant's interaction with the application will be monitored by the facilitator, present in the same room. The data logger will monitor the sessions in the same room. The test sessions will be recorded on video with a camera, and the gameplay will be recorded inside the headset during the session.

The facilitator will brief the participants on the application and instruct the participant that they are evaluating the application, rather than the facilitator evaluating the participant. Participants will sign an informed consent that acknowledges: the participation is voluntary, that participation can cease at any time, and that the session will be videotaped but their privacy of identification will be safeguarded. The facilitator will ask the participant if they have any questions.

Participants will complete a pretest background information questionnaire. At the start of each task, the facilitator will explain the task to the participant, and the participant will begin the task once the explanation has been understood.

The facilitator will instruct the participant to 'think aloud' so that a verbal record exists of their interaction with the application. The facilitator will observe and enter user behavior, user comments, and system actions in the data logging document.

After all task scenarios are attempted, the participant will complete the post-test questionnaire.

A.1.3 Roles

The roles involved in the pilot test are as follows. An individual may play multiple roles.

A.1.3.1 Trainer

- Provide training overview prior to usability testing.

A.1.3.2 Facilitator

- Provides an overview of the study to participants.
- Defines usability and purpose of usability testing to participants.
- Assists in the conduct of participant and observer debriefing sessions.
- Responds to participant's requests for assistance.

A.1.3.3 Data logger

- Records participant's actions and comments.

A.1.4 Ethics

All persons involved with the usability test are required to adhere to the following ethical guidelines:

- The performance of any test participant must not be individually attributable. Individual participants' names should not be used in reference outside the testing session.
- A description of the participant's performance should not be reported to his or her manager.

A.1.5 Tasks

- The participant goes through the first steps in the menu and calibrates the exoskeleton up to the vision calibration menu, using either the controllers or the pointer to navigate in the menu, depending on his or her group.

- The participant completes the calibration and selects the "story" game mode, using the other navigation method according to his or her group.
- The participant's objective is to complete the story mode. If for any reason he or she fails to complete the game, further tasks will be completed individually outside the “story” game mode.
- The participant moves through the game using movement mode 1 or 2 according to his or her group for half the game, and moves in the other mode for the other half.
- Once all the above tasks have been completed, the participant will test the 3rd walking in place mode.

Precise test protocols for groups A and B can be found in the next section A.2.

A.1.6 Metrics

Task success rates, time to understand what is expected, misunderstanding rates, and subjective evaluations will be used. Time-to-completion of scenarios will also be collected.

A.1.6.1 Task completion

The task is completed when the participant indicates that the scenario objective has been reached (successfully or unsuccessfully), or when the participant requests and receives sufficient guidance for the task to be considered a failure.

A.1.6.2 Subjective evaluations

Subjective evaluations regarding ease of use and satisfaction will be collected via questionnaires, during the session via reactions made by the participant, and during debriefing at the conclusion of the session. The questionnaires will utilize free-form responses and rating scales.

A.1.6.3 Task Completion time

The time to complete each task, not including subjective evaluation duration, will be recorded.

A.1.7 Reporting results

The pilot test report will be provided once completed. It will consist of a report and presentation of the results. It will assess usability and feasibility measures against objectives, subjective assessments, specific usability issues, and recommendations for resolution. The report is due by 18.08.2023.

A.2 Protocol

1. Explanation of the project and of the test session:
   (a) Explain the purpose of the project to the participant.
   (b) Explain to the participant what questions we want to answer following these pilot tests:
      i. Are both "walking in place" modes tolerated, which mode is more popular, and do they induce cybersickness? If so, is the anti-cybersickness mode tolerated and effective?
      ii. Is using the pointer to navigate in the menus tolerated/preferred over using controllers? And more generally, is it inconvenient not to use controllers inside the game?
      iii. What is the impact on motivation and engagement of the rehabilitation video game compared with the classic repetitive rehabilitation game?
      iv. Is the complete system (exoskeleton, virtual reality, and video game) tolerated and comfortable?
   (c) Explain to the participant the different games the participant will be playing.
   (d) Explain to the participant the different modes of "walking in place" for moving in the game.
   (e) Explain to the participant the two ways of navigating in the menus (pointer and controllers).
   (f) Explain that the participant's entire body will be tracked and transcribed into the game in the form of an avatar (and explain the calibration with the thumb up).
2. The participant must complete the pre-test questionnaire.
3. Take participant measurements and calibrate the exoskeleton.
4. Training session:
   (a) Perform a training session with the exoskeleton and the participant to check the calibration and confirm that the participant is comfortable.
   (b) Perform training with the virtual reality headset and the participant in order to get used to it and make sure it's properly calibrated and comfortable.

5. Test session:

   (a) Ask the participant to "think aloud" during the session so that there is a verbal record of his/her interaction with the application and it's easier to follow his/her progress during the session.

   (b) Once everything is ready, the game can be launched by the participant (Choose the language the participant wants for the session and the correct group version of the game).

   (c) The participant goes through the first steps in the menu and calibrates the exoskeleton up to the avatar calibration menu, using either the controllers (group A) or the pointer (group B) to navigate in the menu.

   (d) The participant completes the calibration and selects the "story" game mode, using either the pointer (group A) or the controllers (group B) navigation method.

   (e) The participant's objective is to complete the story mode. If for any reason he or she fails to complete the game, further tasks will be completed individually outside the "story" game mode.

   (f) The participant moves through the game using "walking in place" mode 2 (group A) or mode 1 (group B) for half the game, and swaps to mode 1 (group B) or mode 2 (group A) for the other half.

   (g) Once all the above tasks have been completed, the participant will test the 3rd "walking in place" mode.

   (h) Once all the above points have been completed and the participant no longer wishes to test anything, he or she can remove the VR headset and exoskeleton.

6. Debrief the test session with the participant:

   (a) Discuss the comments and reactions the participant had during the session (Example: "During this task, I noticed you were having problems with ..., can you explain what happened?").

   (b) Ask the participant if he or she has anything to add.

7. The participant must complete the post-test questionnaire.

A.3 Questionnaires

The questionnaires used during the test session can be found here:

- Pre-test questionnaire (English version): `https://docs.google.com/forms/d/e/1FAIpQLSdCPZsPNYX8SHR` `viewform?usp=sf_link`

- Pre-test questionnaire (French version): https://docs.google.com/forms/d/e/1FAIpQLSdW-QKTwcoF-Ph
viewform?usp=sf_link

- Post-test questionnaire (English version): https://docs.google.com/forms/d/e/1FAIpQLSebE6AHv3Mzmp
viewform?usp=sf_link

- Post-test questionnaire (French version): https://docs.google.com/forms/d/e/1FAIpQLScZSlRFqwNJOvu
viewform?usp=sf_link

Appendix B

Results

B.1 Cybersickness results

Participant 1	Physio	Group A
Symptoms	Pre-test Score	Post-test Score
General Discomfort	0	1
Fatigue	0	1
Headache	0	0
Eye Strain	0	1
Difficulty Focusing	0	0
Increased Salivation	0	0
Sweating	1	2
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	0
Blurred vision	0	1
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	1	3
Oculomotor subscore (o)	0	4
Disorientation subscore (d)	0	1
Weighted nausea score (N)	9,54	28,62
Weighted Oculomotor score (O)	0	30,32
Weighted disorientation score (D)	0	13,92
Total SS Score	3,74	29,92

(a) SSQ results of participant 1

Participant 2	Autonomyo	Group B
Symptoms	Pre-test Score	Post-test Score
General Discomfort	0	1
Fatigue	1	1
Headache	0	0
Eye Strain	1	1
Difficulty Focusing	0	0
Increased Salivation	0	0
Sweating	0	1
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	0
Blurred vision	0	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	0	2
Oculomotor subscore (o)	2	3
Disorientation subscore (d)	0	0
Weighted nausea score (N)	0	19,08
Weighted Oculomotor score (O)	15,16	22,74
Weighted disorientation score (D)	0	0
Total SS Score	7,48	18,7

(b) SSQ results of participant 2

Figure B.1: Results for the 16 questions on the SSQ questionnaire for participants number 1 and 2 before and after the test.

Participant 3	Physio	Group A
Symptoms	Pre-test Score	Post-test Score
General Discomfort	0	0
Fatigue	0	0
Headache	0	0
Eye Strain	0	2
Difficulty Focusing	1	2
Increased Salivation	0	0
Sweating	1	2
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	1
Blurred vision	0	1
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	1
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	1	2
Oculomotor subscore (o)	1	5
Disorientation subscore (d)	1	5
Weighted nausea score (N)	9,54	19,08
Weighted Oculomotor score (O)	7,58	37,9
Weighted disorientation score (D)	13,92	69,6
Total SS Score	11,22	44,88

(a) SSQ results of participant 3

Participant 4	Autonomyo	Group B
Symptoms	Pre-test Score	Post-test Score
General Discomfort	1	1
Fatigue	1	2
Headache	0	2
Eye Strain	1	1
Difficulty Focusing	1	0
Increased Salivation	0	0
Sweating	0	0
Nausea	0	1
Difficulty Concentrating	0	1
Fullness of the head	0	0
Blurred vision	0	1
Dizzy (eyes open)	0	2
Dizzy (eyes closed)	0	1
Vertigo	0	1
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	1	3
Oculomotor subscore (o)	4	8
Disorientation subscore (d)	1	6
Weighted nausea score (N)	9,54	28,62
Weighted Oculomotor score (O)	30,32	60,64
Weighted disorientation score (D)	13,92	83,52
Total SS Score	22,44	63,58

(b) SSQ results of participant 4

Figure B.2: Results for the 16 questions on the SSQ questionnaire for participants number 3 and 4 before and after the test.

Participant 5	Autonomyo	Group A
Symptoms	Pre-test Score	Post-test Score
General Discomfort	0	2
Fatigue	1	2
Headache	0	1
Eye Strain	1	3
Difficulty Focusing	0	0
Increased Salivation	0	0
Sweating	0	3
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	1
Blurred vision	0	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	0	5
Oculomotor subscore (o)	2	8
Disorientation subscore (d)	0	1
Weighted nausea score (N)	0	47,7
Weighted Oculomotor score (O)	15,16	60,64
Weighted disorientation score (D)	0	13,92
Total SS Score	7,48	52,36

(a) SSQ results of participant 5

Participant 6	Autonomyo	Group B
Symptoms	Pre-test Score	Post-test Score
General Discomfort	0	0
Fatigue	0	1
Headache	0	1
Eye Strain	0	0
Difficulty Focusing	0	0
Increased Salivation	0	0
Sweating	0	0
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	1
Blurred vision	0	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	0	0
Oculomotor subscore (o)	0	2
Disorientation subscore (d)	0	1
Weighted nausea score (N)	0	0
Weighted Oculomotor score (O)	0	15,16
Weighted disorientation score (D)	0	13,92
Total SS Score	0	11,22

(b) SSQ results of participant 6

Figure B.3: Results for the 16 questions on the SSQ questionnaire for participants number 5 and 6 before and after the test.

Participant 7	Autonomyo	Group A
Symptoms	**Pre-test Score**	**Post-test Score**
General Discomfort	0	0
Fatigue	1	1
Headache	0	0
Eye Strain	0	0
Difficulty Focusing	1	1
Increased Salivation	0	0
Sweating	1	2
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	0	0
Blurred vision	0	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	1	2
Oculomotor subscore (o)	2	2
Disorientation subscore (d)	1	1
Weighted nausea score (N)	9,54	19,08
Weighted Oculomotor score (O)	15,16	15,16
Weighted disorientation score (D)	13,92	13,92
Total SS Score	14,96	18,7

(a) SSQ results of participant 7

Participant 8	Autonomyo	Group B
Symptoms	**Pre-test Score**	**Post-test Score**
General Discomfort	0	0
Fatigue	1	1
Headache	0	0
Eye Strain	1	1
Difficulty Focusing	0	0
Increased Salivation	0	1
Sweating	1	1
Nausea	0	0
Difficulty Concentrating	0	0
Fullness of the head	1	0
Blurred vision	1	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	1	1
Burping	0	0
Nausea subscore (n)	2	3
Oculomotor subscore (o)	3	2
Disorientation subscore (d)	2	0
Weighted nausea score (N)	19,08	28,62
Weighted Oculomotor score (O)	22,74	15,16
Weighted disorientation score (D)	27,84	0
Total SS Score	26,18	18,7

(b) SSQ results of participant 8

Figure B.4: Results for the 16 questions on the SSQ questionnaire for participants number 7 and 8 before and after the test.

Participant 9	Autonomyo	Group B
Symptoms	**Pre-test Score**	**Post-test Score**
General Discomfort	0	0
Fatigue	0	0
Headache	1	0
Eye Strain	1	1
Difficulty Focusing	0	1
Increased Salivation	0	0
Sweating	0	1
Nausea	0	0
Difficulty Concentrating	0	1
Fullness of the head	0	1
Blurred vision	0	0
Dizzy (eyes open)	0	0
Dizzy (eyes closed)	0	1
Vertigo	0	0
Stomach awareness	0	0
Burping	0	0
Nausea subscore (n)	0	2
Oculomotor subscore (o)	2	3
Disorientation subscore (d)	0	3
Weighted nausea score (N)	0	19,08
Weighted Oculomotor score (O)	15,16	22,74
Weighted disorientation score (D)	0	41,76
Total SS Score	7,48	29,92

(a) SSQ results of participant 9

Participant 10	Physio	Group A
Symptoms	**Pre-test Score**	**Post-test Score**
General Discomfort	0	2
Fatigue	0	2
Headache	0	1
Eye Strain	0	2
Difficulty Focusing	0	1
Increased Salivation	0	0
Sweating	1	1
Nausea	0	2
Difficulty Concentrating	1	1
Fullness of the head	0	0
Blurred vision	0	2
Dizzy (eyes open)	0	1
Dizzy (eyes closed)	0	0
Vertigo	0	0
Stomach awareness	0	2
Burping	0	1
Nausea subscore (n)	2	9
Oculomotor subscore (o)	1	11
Disorientation subscore (d)	0	6
Weighted nausea score (N)	19,08	85,86
Weighted Oculomotor score (O)	7,58	83,38
Weighted disorientation score (D)	0	83,52
Total SS Score	11,22	97,24

(b) SSQ results of participant 10

Figure B.5: Results for the 16 questions on the SSQ questionnaire for participants number 9 and 10 before and after the test.

Appendix C

Source code

The GitHub repository can be found here:
`https://github.com/NicolasVial/Nicolas-Vial-internship-Autonomyo`
The repository contains all the code for this project.

Appendix D

Game-play video

A video of the game-play can be found here (with the setup that uses crutches instead of the safety frame):
`https://www.youtube.com/watch?v=If1hgb5agkM`
The video of the game may have weird effects and aliasing but this is due to the recording. The actual game doesn't have such issues.