Master Thesis

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University
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F3

Faculty of Electrical Engineering
Department of Computer Graphics and Interaction

Exercise for the elderly in VR

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Field of study: Open Informatics
Subfield: Human Computer Interaction
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MASTER‘S THESIS ASSIGNMENT

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II. Master’s thesis details

Master’s thesis title in English:

Exercise for the elderly in VR

Master’s thesis title in Czech:

Cvičení pro seniory ve VR

Guidelines:

Seniors in the residential care homes regularly perform various rehabilitation exercises to maintain mobility. One of these exercises is walking on a sensorimotor walkway. The purpose of this thesis is to investigate the possibilities of using VR for this exercise - primarily to increase the attractiveness of the exercise and also to establish social interaction of the exercise group.

1) Familiarize yourself with a common exercise procedure, i.e., walking along a predefined sensorimotor pathway. Next, analyze possible methods of sensing the movement of the lower half of the user's body suitable for application in a nursing home.

2) Design and build a prototype VR application to verify the feasibility of walking on a sensorimotor walkway with a VR headset deployed. Test the prototype with users (no target group required). During testing, focus on the user's sense of accuracy and believability of the visualization of walking in VR.

4) Design a pleasant, colorful environment (park bench, lake view, moving animals, ...) to place the VR version of the walkway. Implement the VR experience for the Oculus Quest platform. Connect with a mobile app to configure and control the VR application. Design and implement a mechanism for scaling the complexity level.

5) Link your solution to a web portal to track user progress [4].

6) Follow the UCD methodology for design and implementation. Test the application with at least five users of the target group.

7) Design a longitudinal (large-scale) study to evaluate the contribution of the VR application for this exercise.

Bibliography / sources:

1] Jason Jerald. 2015. The VR Book: Human-Centered Design for Virtual Reality. Association for Computing Machinery and Morgan & Claypool, New York, NY, USA.
2] Steven M. LaValle - Virtual Reality, Cambridge University Press 2016
3] T. Lowdermilk, User-Centered Design, O’Reilly Media, 2013
4] Leoš Řeháček, Aplikace pro sběr a analýzu dat z VR tréninkových aplikací. DP ČVUT FEL, 2024.

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Date of assignment receipt

Student's signature

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I would like to express my gratitude to my supervisor Ing. David Sedláček, Ph.D., who kindly and patiently guided me throughout this thesis and for his encouragement that motivated me to turn this thesis in on time.

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Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

In Prague, 24. May 2024

Abstract

Seemingly minor incidents, such as tripping or slipping, can be life-changing. This is particularly true for the elderly, as the risk and severity of fall-related injuries increase with age. In recent years, fall prevention has become a critical area of research and many techniques and methods were proposed. With the emergence of Virtual Reality (VR) technologies many possibilities to enhance these techniques have become available.

This thesis explores the potential use of virtual reality technology in enhancing the sensorimotor walkway exercise for elderly individuals. The utilization of VR aims to increase exercise attractiveness and social interaction while stimulating the somatosensory system of the individual.

During the thesis a prototype VR application to verify the importance of leg tracking was developed and tested. This was followed by the development and testing of the PhysioBridge application. For the patients, it provides a comprehensive VR experience during the exercise. For the physiotherapist a control application for Android smartphone was developed. The thesis concludes with the design of large-scale study to research the contribution of the virtual reality for the sensorimotor walkway exercise.

Keywords: virtual reality, sensorimotor exercise, elderly, retirement home, Oculus Quest

Supervisor: Ing. David Sedláček, Ph.D.
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Abstrakt

Zdánlivě drobné nehody, jako jsou zakopnutí či uklouznutí, mohou změnit lidský život. To platí zejména pro starší osoby, protože riziko úrazů způsobených pádem a jejich závažnost se s věkem zvyšuje. V posledních letech se prevence pádů stala kritickou oblastí výzkumu a bylo navrženo mnoho technik a metod prevence. S nástupem technologií virtuální reality (VR) se objevilo mnoho možností, jak tyto techniky ještě vylepšit.

Tato práce se zabývá potenciálním využitím virtuální reality pro obohacení cvičení na senzomotorického chodníčku. Využití virtuální reality má za cíl zvýšit atraktivitu cvičení a sociální interakci a zároveň stimulovat somatosenzorický systém jedince.

V průběhu práce byl vyvinut a otestován prototyp VR aplikace pro ověření významu sledování pozice nohou. Následoval vývoj a testování aplikace PhysioBridge. Ta během cvičení pacientům poskytuje komplexní VR zážitek. Pro fyzioterapeuta byla vytvořena ovládací aplikace pro Android smarpthone. V závěru práce je navržena rozsáhlá studie, jejímž cílem je výzkum přínosu virtuální reality pro cvičení na senzomotorickém chodníčku.

Klíčová slova: virtuální realita, sensomotorické cvičení, senioři, domov pro seniory, Oculus Quest

Překlad názvu: Cvičení pro seniory ve VR

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Introduction

A seemingly innocent incident such as tripping on a sidewalk or slipping on a wet floor can change the course of person's life. This is especially true for older people as the risk of falling and the severity of fall-related issues rises with age[1]. Therefore, in recent years, many different fall prevention techniques and exercises have been developed and researched to reduce the risk of falls in the elderly.

As virtual reality (VR) devices have become more affordable, numerous industries, including the healthcare sector, are now exploring the possibilities of using the virtual reality. Many studies have shown that integrating virtual or mixed reality into fall prevention exercise can have a positive effect on physical functions in the elderly[2].

The purpose of this thesis is to investigate the possibility of using virtual reality for the sensorimotor walkway exercise, regularly performed at the Nová Slunečnice retirement home in Prague. The primary goal of using virtual reality is to increase the attractiveness of the exercise as well as the social interaction of elderly. Secondarily, by using virtual reality to alter the visual and auditory perception, the user is forced to rely more on the other senses to perform the exercise correctly. And, as the goal of the sensorimotor walkway exercise is to stimulate the somatosensory system, the use of virtual reality, as a mean of altering visual and auditory inputs, could potentially improve the overall benefits of the exercise.

Initially, a prototype VR application was designed, built and tested. The goal was to verify the viability of walking with virtual reality headset deployed. This prototype incorporated an experimental leg tracking approach utilizing the MediaPipe pose landmark detection solution.

Based on the insights gained from user testing of the first prototype, a second VR application was developed. This version primarily focuses on providing a full virtual reality experience during the sensorimotor walkway exercise. Simultaneously, a control application for Android smartphone was developed, enabling the operator to control and observe the virtual reality application. User testing was conducted for both the virtual reality application and the control application, both of which are later referred to as the PhysioBridge application.

The thesis concludes with design of a longitudinal study aimed to evaluate the impact of virtual reality on the exercise outcomes.

Thesis structure

Chapter 1 provides an introduction to the medical background related to the thesis topic. The sensorimotor walkway exercise, for which the PhysioBridge application is intended, is also described in this chapter.

Chapter 2 introduces the topic of virtual reality. It presents some general considerations for VR development, examines the topic of VR sickness and analyses the state of the art methods used for tracking objects in 3-dimensional space.

Chapters 3 and 4 focus on the leg tracking prototype application. In the chapter 3, the main ideas behind the proposed solution are explained along with the implementation process. Chapter 4 describes the testing process of the prototype and presents the gather data.

Chapters 5, 6 and 7 describe the step-by-step design, implementation, testing and evaluation of the developed PhysioBridge application.

Chapters 8 discusses the developed application and potential future improvements. Second part of this chapter presents the design of the large-scale study which aims to evaluate the contribution of virtual reality for the sensorimotor walkway exercise.

Chapter 1

Medical background

According to the World Health Organization (WHO)[3], an estimated 684 000 individuals die from falls each year. This makes falls the second leading cause of unintentional injury deaths worldwide. With adults older than 60 years of age suffering the greatest number of fatal falls, this makes age a key risk factor for falls.

In addition to physical injuries, the consequences of falls may have a significant impact on a person's mental health and overall function. Postural instability or prior fall experiences can lead to fear of falling and anxiety during normal daily activities[4]. This can result in reduction of activity, decreased mobility and loss of independence in elderly.

Additionally, fall-related injuries entail social consequences. First, as briefly mentioned in the previous paragraph, there are social consequences on an individual level. Those include the direct impact on an elderly person's life, such as social isolation. Secondly, there is a societal aspect to these consequences, which may not be apparent at first glance. Fall related injuries are costly, especially when the falls lead to injuries requiring hospitalization and rehabilitation[5]. This results in a strain on healthcare resources, increased demand for long-term care services, and challenges in providing adequate support for elderly individuals and their caregivers.

In conclusion, considering everything discussed earlier, it becomes evident that prevention of falls is far better than their management[6]. This chapter will discuss the topic of fall prevention and the training on a sensorimotor walkway.

1.1 Falls prevention

Falls can hardly be attributed to a single risk factor as a range of various factors, such as demographic, physical, psychological or environmental, contribute to falls risk[7]. Despite the large amount and variety of risk factors, many falls can be avoided through implementation of various fall prevention techniques. These may range from regular training sessions, through home assessment and modifications, to seemingly trivial measures such as wearing suitable footwear.

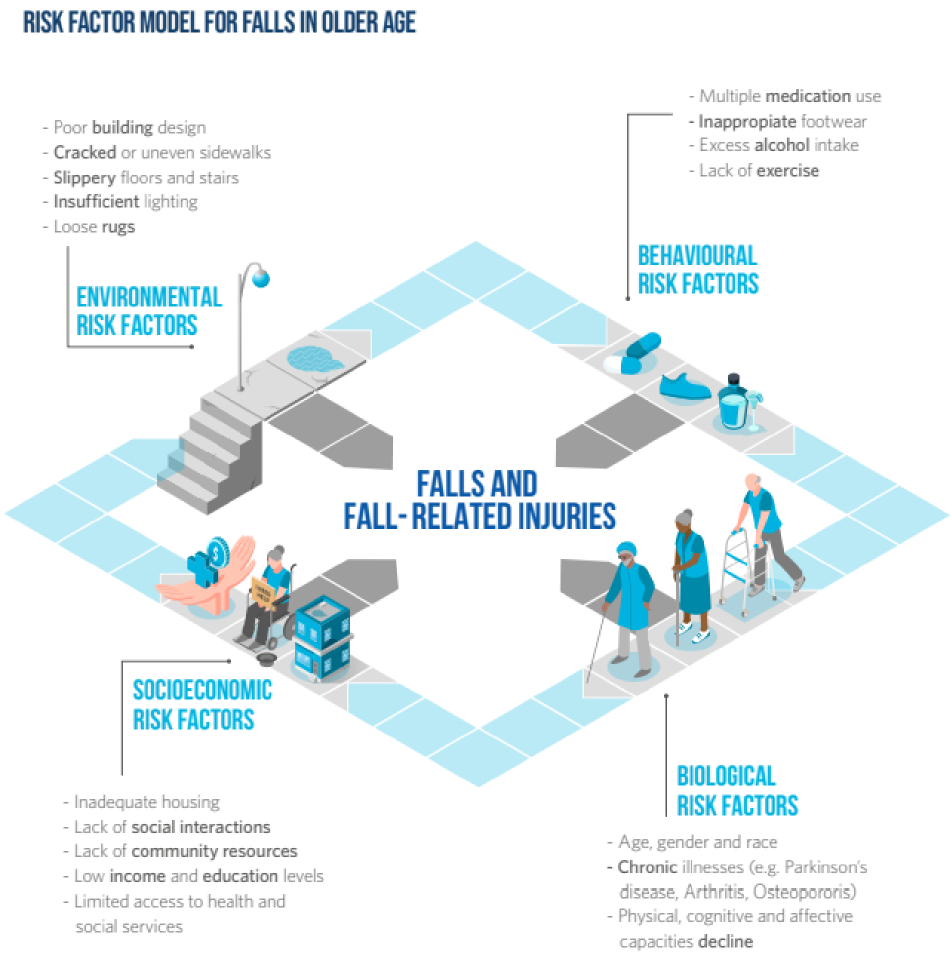

Figure 1.1: Illustration of a risk factor model for falls in older age from the WHO's Step Safely publication[7]

Even though various fall prevention techniques are available, balance training is among the most recommended ones[7]. Sensorimotor training, as indicated by numerous studies[8], demonstrates significant improvement in balance, mobility, and overall proprioceptive function. Therefore it is commonly included in balance exercise routines.

1.2 Sensorimotor walkway

There are numerous different known and commonly used sensorimotor exercises, however, the sensorimotor walkway is a specialty of the Nová Slunečnice retirement home. One of the local physiotherapists came up with the idea of combining the parallel bars system, commonly used for gait training, with attached carpets designed to stimulate the nerve endings in the patients' feet. This sensorimotor walkway is regularly used at the retirement home as a part of the sensorimotor training sessions.

Figure 1.2: Picture of the sensorimotor walkway from the Nová Slunečnice retirement home

These training sessions usually consist of a small group of two to five patients and a physiotherapist, who leads the training. Patients perform multiple proprioceptive exercises including the walk on a sensorimotor walkway. In the course of this exercise the patient walks back and forth on the different materials wearing nylon socks for maximum surface feel. On each carpet, the patient is supposed to stop and step from one foot to the other, focusing on the sensations they perceive. According to the retirement home, this exercise should serve the following purposes:

- Stimulation of nerve endings
- Enrichment of perception and brain activity
- Positive influence on the entire musculoskeletal system
- Stability and balance improvement
- Improved blood circulation in the lower limbs
- Inducing a good mood and a feeling of lightness

Chapter 2

Virtual reality (VR)

Immersive technologies play a big part in today's rapidly evolving world of technology. Head mounted displays are currently being produced by multiple companies, thus becoming more available to the general public. This has led to a wider adoption of virtual reality in various fields, including education, training simulations, prototyping, health care and many more[9].

Although there are several different devices with various capabilities available, the basic terminology and underlying technology remains the same. This allows us to describe some general considerations for VR development, as well as virtual environment design.

This chapter will focus on explaining the basic terminology related to virtual reality as well as outline things to look out for when developing a virtual reality application. In the last part of this chapter, there is a short overview of current state of the art options to track the position of real world objects and displaying them in the virtual world.

2.1 Extended reality (XR)

The set of immersive technologies, blurring the difference between the real and virtual worlds, is commonly referred to as extended reality. Although this term has become popular in the recent years, the concept of virtual reality continuum was already formed 30 years ago by Paul Milgram[10]. The virtual reality continuum introduces the terms that today fall under the extended reality category, including augmented reality, augmented virtuality and virtual reality. The work also defines the term mixed reality, which encompasses both the augmented reality and virtuality.

- **Augmented reality (AR)** is the term closest to the real environment on the reality-virtuality continuum. It includes cases where display of an otherwise real environment is *"augmented"* by means of virtual (computer generated) content.

- **Augmented virtuality (AV)** can be viewed as the opposite or converse of augmented reality. Compared to AR, AV refers to the overlay of real world objects into a mostly virtual environment.
- **Mixed reality (MR)** is the umbrella term for AR and VR. Mixed Reality environments are neither purely virtual nor real. It is simply an environment where real world and virtual objects are presented together within a single display.
- **Virtual reality (VR)** is at the very edge of the reality-virtuality continuum and describes a fully synthetic world in which the observer is completely immersed in.

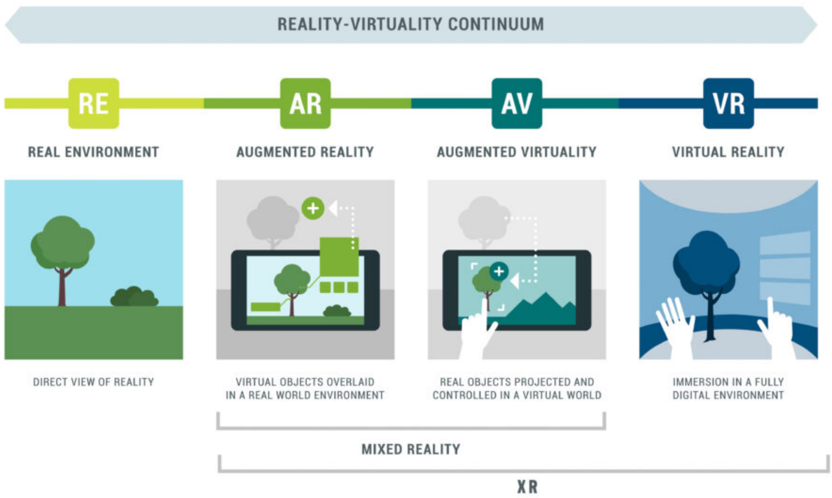

Figure 2.1: Illustration of the reality-virtuality continuum with examples from the CreatXR website[11]

Many currently available head mounted display devices are capable of providing the whole range of extended reality experiences. This freedom of choice brings virtually unlimited possibilities for the creators while developing their extended reality experiences. However, this also brings new challenges to the design phase, where the creator has to consider multiple design guidelines.

2.2 Immersion and presence

When designing any user experience, whether virtual or not, emotions play a crucial role. As humans are highly emotional beings, influencing their emotions can affect their decision making[12]. While designers often focus on evoking positive emotions in order to make their product more likeable, by having a bad UX design the opposite can easily be achieved. This is even more important to take into consideration when designing for virtual reality devices.

Humans experience reality through senses, including internal sensations like hunger and pain, as well as external stimuli such as smell, touch, and sight. Based on the information provided by senses, the human brain gains understanding of the environment and formulates decisions accordingly. The idea behind virtual reality devices is to provide artificial stimuli to the senses and thus try to trick the brain into perceiving a non-existent environment[13]. This gives virtual reality the ability to evoke emotions through enhanced presence and provides the designers with a chance for a greater emotional impact[14]. This enhanced presence can be easily broken by several factors, however when done correctly, the emotional involvement can be profound. Therefore, it is even more important to thoroughly understand the basics of VR design. The most fundamental terms to understand are immersion and presence.

- **Immersion** describes the extent to which the device is capable of delivering an inclusive, extensive, surrounding and vivid illusion of reality to the senses of a human participant[15].
- **Presence** is an psychological state that could be described as a sense of being in the virtual environment[16]. Presence can be also described as a function of both the user and immersion[17].

In other words, it is necessary to realize, that although we can control immersion, we can never completely control the presence of user in the virtual environment. However, focusing on greater immersion provides greater potential for the user to feel present in the virtual world.

Closely connected and equally important term is **break-in-presence**. Those are moments when the illusion of being in a virtual environment breaks down and can destroy the entire VR experience[17]. Sometimes it is impossible to prevent such breaks, for example if a real world phone rings or user starts tripping on a wire. However, some of these breaks, such as losses of tracking or freezing of the display, can be prevented.

To summarize the above, in process of designing any virtual experience it is important to focus on maximizing presence. Since it is not possible to control presence entirely, we can focus on maximizing the immersion and minimizing breaks-in-presence. The following subsections try to describe some of the issues to look out for.

Stable sense of place

One of the most crucial aspects of maintaining presence in virtual reality is maintaining a stable sense of place[17]. To achieve that, the virtual environment should resemble the experiences from real world. This is related mainly to the visual and auditory cues the user receives. For example the user should be able to hear running water when near a river.

Self-Embodiment

Many VR experiences contain only depiction of the user's hands and not the whole body. Although depiction of the whole body is not required for the user to feel present, it can very well strengthen the user's presence in the virtual world[18]. When depicting the virtual body, it does not need to be an exact replica, as long as it keeps the basic humanoid structure. However, what is important for the sense of body ownership is that the sense of self-location corresponds with the locations of avatar body parts. If the user feels detached from the body, it will cause a break-in-presence.

Uncanny Valley

Although receiving little attention when it was originally published in 1970, Uncanny Valley[19] is practically a basic knowledge of any UX designer. It proposes a nonlinear relation between human likeness of an entity and the perceiver's affinity towards it. This needs to be taken into consideration, especially when creating realistic virtual environments.

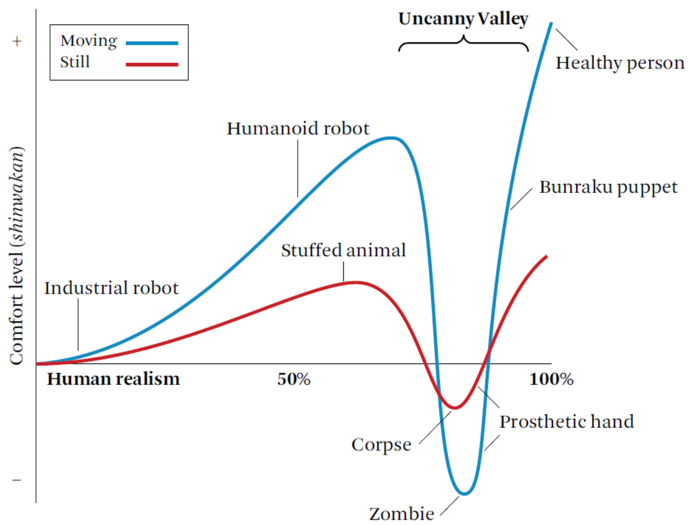

Figure 2.2: Illustration of the Uncanny Valley theory from The VR book[17]

Interactions

Similarly, to maintaining a stable sense of place, realism is also important when it comes to interactions in the virtual world. In order to maintain presence, users should be able to interact with virtual objects in a way that feels natural and intuitive[20].

The most prominent types of interactions are locomotion and object manipulation. Locomotion in VR is a difficult topic, but in this thesis, it is mostly irrelevant, as the movement in the real world is mapped 1:1 to movement in virtual world and thus there is no need for artificial locomotion techniques.

Even if manipulation is designed to be intuitive, it is still beneficial to provide the user with constraints to guide actions and immediate and useful feedback[17]. Visual feedback in the form of object highlighting or some form of haptic feedback are the most common.

Hardware limitations

The hardware, on which the VR experience is running, basically dictates the fidelity of the virtual experience. There are many variables that need to be accounted for - the most basic ones being the screen refresh rates, latency and tracking update rates and accuracy[17].

Even though computer graphics are more than powerful enough to run realistic virtual experiences, the headset still needs to be connected to the computer. This can be achieved through wired as well as wireless connection, although both of these options have their drawbacks. With the wired connection the user has limited range of movement, the wireless connection can cause stuttering through a limited bandwidth.

The best option from the UX point of view is to run the experience on the headset itself. However, as the headset is not as powerful as a personal computer, the environments and sometimes the whole experiences often need to be simplified.

2.3 VR sickness

Although virtual reality devices experienced multiple advancements, VR sickness is still a relatively common issue. At least one third of users experience some kind of discomfort related to the use of virtual reality[21]. VR sickness is often referred to with multiple names like motion sickness, simulator sickness or cybersickness. No matter the terminology, the health issues related to the use of virtual reality are most commonly eye fatigue, disorientation and nausea[22].

In early studies, the VR sickness symptoms were thought to only originate from poor performance of the hardware. However, even with continuous performance increases throughout the years, the VR sickness has not been resolved completely. This basically eliminates the probability of the hardware being the only cause. In a recent scientific review[22] the causes of VR sickness were divided into 3 main groups - hardware, content and human factors.

2.3.1 Hardware

The hardware the virtual reality is running on does not only directly affect the visual fidelity but also the overall user experience. Hardware factors that can influence VR sickness are often related to the display type, the field of view of the display device, the refresh rate, and latency.

Most of the factors causing VR sickness that are directly linked to the hardware and cannot be influenced by the developer. These might include flicker, weight or fit of the VR device. A factor partially connected to the hardware which can be influenced is the latency.

There is no official guideline stating the exact latency that should be used when designing VR experiences. However, there are numerous recommendations based on previous experiences or research. Based on a research on latency impact on quality of experience in virtual reality simulator[23], latencies over 35 milliseconds should be avoided. According to John Carmack[24], co-founder of the video game company id Software, the latency should be below 50 milliseconds to feel responsive and recommended value is less than 20 milliseconds. No matter the exact number, the end goal is to keep latency as low as possible. This can either be achieved by using more powerful VR device or by meticulous software optimizations.

2.3.2 Content

One of the most common causes of VR sickness is seeing the moving content inside VR headset when stationary in real life. This creates a sensory conflict which in turn often causes discomfort. However, this is not relevant for the topic of this thesis as virtual movement will not be utilized.

Another area to consider is the level of realism. A higher realism often does not correlate with a better user experience. Instead, a research[22] has shown that participants who experienced more realistic virtual environment tended to show an increased level of discomfort.

2.3.3 Human factors

Research into the human factors of VR sickness is still ongoing and has produced mixed results, when it comes to factors like age and gender. Although some studies showed that women are more susceptible to VR sickness, the correlation between gender and level of discomfort is not significant.

One of the factors that are definitely linked to VR sickness is susceptibility to motion sickness as people suffering from motion sickness often report higher discomfort. The second factor is previous VR experience, as continuous VR exposure can reduce the severity of VR sickness[22].

2.4 Tracking objects in 3D space

A VR experience without any means of position and movement tracking would never truly make the user feel present in the virtual world. Not only that it would make them feel like they were watching a movie, moreover without any form of tracking the view in the HMD would be frozen and not interactive. Therefore, some form of tracking is essential for any meaningful VR experience.

When talking about the topic of object tracking in 3-dimensional space in general, there are several methods using various types of sensors. The most common types of object tracking will be described below. Some of these methods can even be combined, creating so called hybrid trackers.

2.4.1 Magnetic

Magnetic object tracking uses magnetic fields to monitor and locate objects. These types of trackers use a base station that emits a magnetic field and sensors that measure intensity of the emitted field[25]. From these measurements the position and orientation of the sensor can be computed.

This method can provide good accuracy as well as low latency and there is no issue with visual occlusion. The drawback of this method is that the accuracy drops rapidly with increasing distance from the base station. Moreover, the use of magnetic fields makes this method very sensitive to any ferromagnetic material[26]. Overall, this method is good for controlled environments, but not well suitable for use elsewhere.

2.4.2 Acoustic

Acoustical trackers use sound as the means of tracking an object. Periodic sound pulses (often ultrasonic) are emitted and picked up by microphones attached to the tracked object. The position is then computed by measuring difference between the times when the sound was emitted and received. Multiple emitters need to be used in order to track position in 3-dimensional space[25].

The main benefit of this method is that the sensors are often small and lightweight, however this is outweighed by the drawbacks. As this method relies on sound, it is very sensitive to any factor that affects the speed of sound, such as humidity or temperature. It is also very sensitive to background noise or occlusion[27], although these might be solved by careful and time consuming calibration.

2.4.3 Inertial

Inertial tracking uses two types of sensors - accelerometers and gyroscopes. Accelerometer is responsible for measuring the linear acceleration and gyroscope measures the relative orientation change. The problem with these sensors is that the measurements are relative to their starting position. Any errors will result in a drift due to them being accumulated over time[26]. The accumulation of the drift is heavily influenced by the quality of the sensors.

The main advantages are that inertial tracking is very inexpensive and can provide high update rates and low latency. As errors accumulate over time it is hard to rely only on inertial tracking to determine position[27]. However, inertial sensors are often useful when combined with other position tracking systems[28].

2.4.4 Optical

Optical tracking is particularly notable among the various techniques, especially in conjunction with virtual reality. Most of the VR headsets use some kind of optical tracking, as it is one of the easier techniques for users to set up. The idea behind optical tracking is to use light to track the position of objects. This can include various methods[28] ranging from passive stereo vision systems to laser solutions like LIDARs. These methods can be divided into two opposite approaches - inside out and outside in.

- **Inside out** uses multiple camera devices mounted on the tracked object. The cameras track features of the surrounding environment and the tracking algorithms then analyse the captured data to determine the current position.
- **Outside in** uses reverse approach, where camera devices are placed in the environment and record features of the target. These features are predefined patterns, that can be used to determine the target's position.

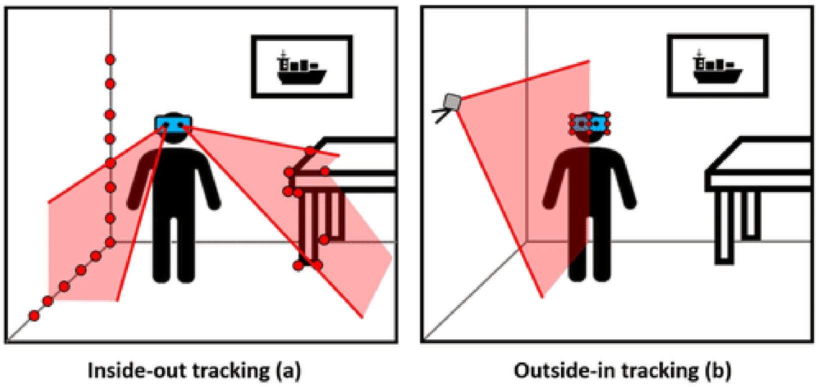

Figure 2.3: Illustration of inside-out (a) vs. outside-in (b) optical tracking[29]

Optical tracking in general has good accuracy[26]. The main limitation of optical tracking systems is their inability to effectively handle visual occlusion. Furthermore, certain optical tracking methods may encounter difficulties operating in low light conditions.

Chapter 3

Prototype for leg tracking in VR

In today's world, not many VR experiences provide full body tracking, especially due to its complexity and financial demands. As mentioned in 2.2, in order to feel present in the VR experience, users do not really need full body tracking. However, most of the VR experiences do not require the user to walk precisely through a given space.

While researching the usage of virtual reality in medical field and walking exercises especially, I found that the focus is put mainly on gait training on a treadmill. As the walking precision is not an essential part of this exercise, it makes sense that there is no full body tracking included. That being said, I was unable to find any study focusing on the importance of leg tracking in therapeutic walking VR experiences.

Therefore, a prototype for leg tracking was built in order to evaluate the importance of leg tracking in the specific use case in connection to the sensorimotor walkway. Secondly, if a leg tracking solution proved to be feasible, it might provide further benefits such as additional data for later progress evaluation and research or the option to implement various gamification elements.

3.1 Prototype design

Since December 2019, when hand tracking was first introduced to the Meta Quest platform[30], tracking technology in head mounted displays has been significantly improved. Meta Quest 2 headset, for which the final application should be implemented, uses the inside out optical tracking approach with four cameras mounted on the headset. However, these cameras cannot be accessed directly and thus causes the developers to be limited to the features provided by Meta XR software development kits (SDKs).

At the time of prototype development, Meta provides a Movement SDK[31] that enables developers to track the upper body of the user and projects plausible lower body movement based on what the upper body is doing.

Although visible to the user, the lower body representation does not accurately reflect the first person's perspective. Unfortunately, a mere approximation is not sufficient for this use case, prompting the necessity for a custom tracking solution.

3.1.1 Requirements

Even though, there are many different approaches for object tracking in virtual reality to choose from, when narrowing the focus to methods applicable within a retirement home, the available options are significantly reduced. Here are the main requirements for the tracking solution that needed to be taken into consideration:

- **Low complexity** - the solution should be easy to set up and use as it adds additional workload on the therapists.
- **Financially affordable** - given the limited budgets typically associated with retirement homes, the use of expensive, ready made solutions is not feasible.
- **Minimal attached hardware** - this is mainly to minimize the setup duration and discomfort of the patient.

3.1.2 Proposed solution

When researching possible methods for full body tracking in virtual reality, there are many seemingly functional and fairly simple solutions originating from the VRChat community. However, these solutions are mainly focused on the VRChat application and not optimized for general use.

The idea behind those solutions is using the combination of single camera device and computer vision algorithms to determine the user's position. The same idea was reused in this prototype, using an Android smartphone as a simple and inexpensive camera and a MediaPipe library providing the algorithm for user's position detection.

- **MediaPipe**[32] is an open-source framework containing pre-trained deep learning models that could be used for a variety of different tasks. It also provides premade solutions with a suite of libraries and tools for quick application of artificial intelligence (AI) and machine learning (ML) techniques.

MediaPipe library provides a solution for detection of 33 body landmarks of a human body in both images and video[33]. Part of the solution is also an implementation for Android platform, which among others outputs body pose landmarks in 3-dimensional world coordinates. The idea of the proposed leg tracking solution is to modify the existing Android application in order to send the data to the prototype VR application. Subsequently, these data need to be calibrated in the virtual world in order to correspond with the user's position.

In conclusion, this approach requires only an Android device with the application for landmarks detection installed. Moreover, no additional hardware would need to be attached to the VR user, making the experience more enjoyable. Lastly, the setup with this approach should be quite easy and straightforward, assuming the only setup steps needing to be done are positioning the camera and calibration.

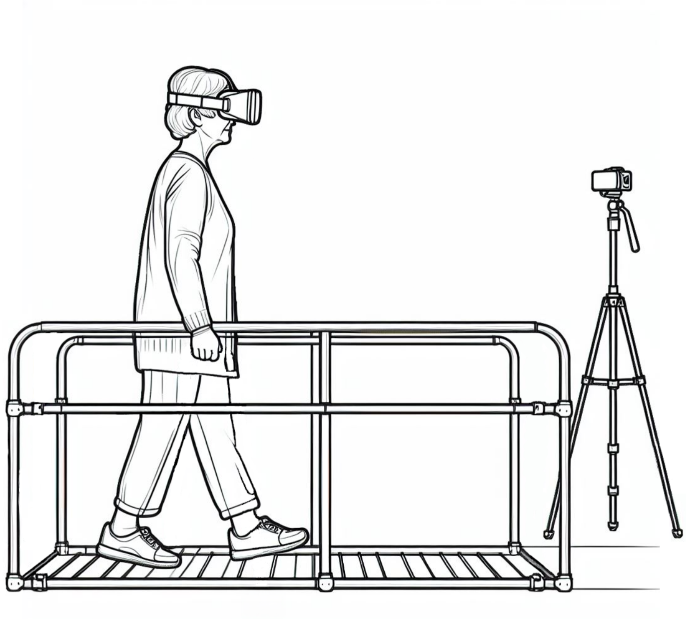

Figure 3.1: Sketch of the proposed leg tracking solution

3.2 Networking

The primary challenge in the development of the proposed solution laid in establishing communication between the MediaPipe Android application and VR prototype. The Android application needed to be able to transfer information about the detected landmarks to Unity environment, used for the prototype development. This section describes the communication between the MediaPipe application (client) and VR application (server) in more detail.

3.2.1 Communication protocol

As mentioned previously, low latency supports an immersive VR experience as well as reduces VR sickness. For that reason, UDP was chosen as the transfer protocol. The biggest drawback of the UDP protocol is its unreliability as it does not check whether the data were successfully delivered. However, this enables the protocol to be especially fast, allowing for low latency in the VR experience. Both the UDP server and client were implemented as a part of the prototype.

A further point to consider was the communication format. As the MediaPipe application is implemented in Kotlin and Unity uses C#, there was a need for a format, that both languages could work with easily. Moreover, it would be helpful if the format was human readable, as this allows for easy debugging. Finally, the transfer size should be as small as possible, in order to reduce transfer time. The decision was made to use the JSON format, as it is widely used, has minimal footprint and could be easily used in both languages.

3.2.2 Automatic IP detection

In order for applications to communicate, the client (MediaPipe) needs to know the IP address of the server (VR). The simplest solution would be to let the user add the address manually, however, this would require the user to have prior technical knowledge and would add another layer of complexity. As quick setup was one of the key requirements, an automatic IP address detection was essential.

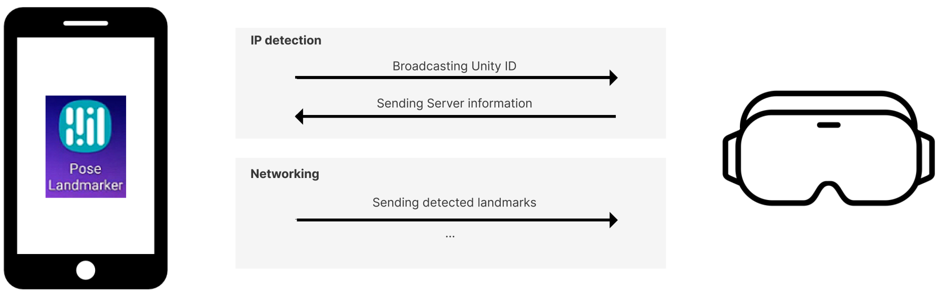

Figure 3.2: Scheme of the UDP communication between the MediaPipe Android application and the VR prototype

One option would be to implement a custom IP address detection algorithm from scratch. Although the algorithm would not be very complex, the exact same functionality is already implemented for Unity in the widely used Mirror Networking library[34]. Moreover, a part of the requirements for the final therapeutic application is to provide a control application and for this, the

Mirror library will be used. Therefore, it was a natural choice to use Mirror in the prototype as well.

Due to the Mirror library being Unity specific, there was no easy way to use this functionality in Kotlin (MediaPipe application). To gain a better understanding of how the Mirror communication works, the Wireshark utility was used to capture the ongoing communication between two Unity instances. The figure 3.2 shows a diagram of the server detection algorithm and subsequent communication in action.

3.3 Projecting landmarks into VR

The Landmarks detection solution from the MediaPipe application outputs each landmark in 3-dimensional world coordinates. This coordinate system is defined by the position of a user's hips and the direction of the camera. Using this representation, it should be guaranteed that the scaling will correspond to the real world. However, it was still necessary to adjust the position and rotation of the detected landmarks in the virtual environment. Secondly, by deriving the model coordinates from a user's hips, there was no information of the shift in the user's position in the real world. Therefore, in addition to the initial calibration it was also necessary to constantly adjust the horizontal position of the model in the virtual environment.

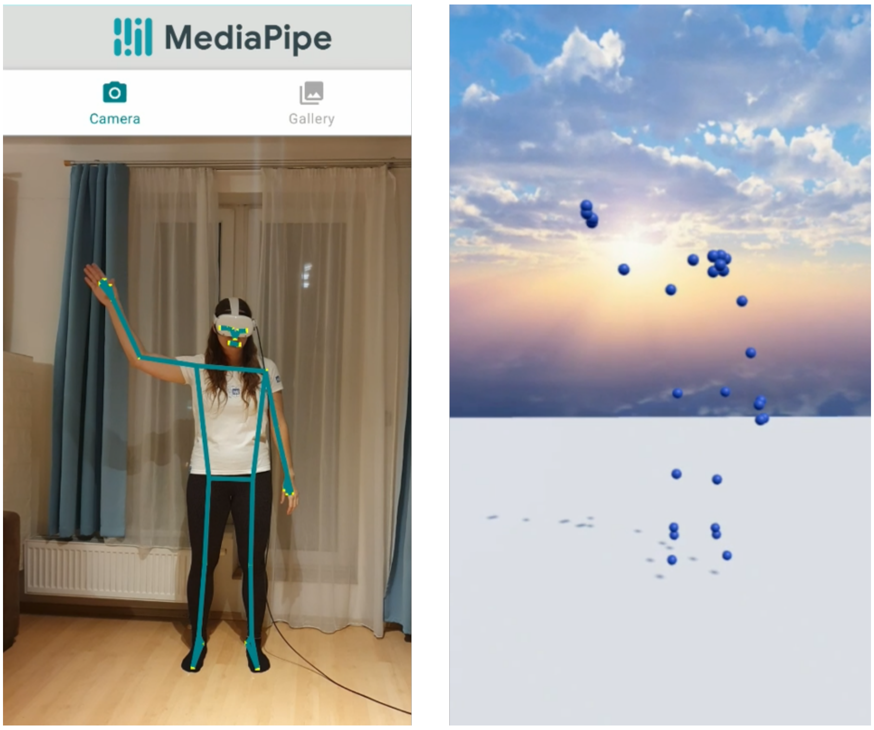

Figure 3.3: Landmarks detected in the MediaPipe application *(on the left)* and their initial representation in the virtual environment *(on the right)*

3.3.1 Calibration

During the calibration, the model's rotation, vertical alignment and distance to the ground are set. As the horizontal alignment requires constant shifting it did not need to be addressed during the calibration process. The overall calibration process is summarized in the following steps.

1. The user extends their right hand to the side and performs a pinch hand gesture to indicate the start of the calibration.
2. In this position user remains for 3 seconds, during which the hand position is measured and averaged.
3. Steps one and two are repeated for the left hand.
4. The landmarks model is rotated according to the averaged positions.
5. The user looks down at their feet and performs a pinch hand gesture using right hand to indicate start of the ground distance calibration.
6. In this position user remains for 3 seconds, during which the ground distance and tolerance for both feet are computed.

3.3.2 Horizontal movement

One of the first implemented solutions for the model's horizontal transition was to shift the detected landmarks according to the position of the VR headset. However, this solution proved to be inaccurate as any small shifts in the head position parallel to the camera resulted in large shifts of the detected landmarks model. This is likely caused by the inaccuracy of depth detection in the MediaPipe Pose Landmarker solution.

Other implemented solution was to shift the detected model according to the approximated position of hips from the Movement SDK for Unity. This reduced the problem with parallel model shifting mentioned previously. However, it turned out that the vertical position of the approximated hips changes significantly with the movement of the arms, resulting in a vertical displacement of the whole model.

Eventually a combination of these two approaches was used. The vertical position is computed from the headset position, whereas the position change on the horizontal axis is obtained from the Movement SDK for Unity.

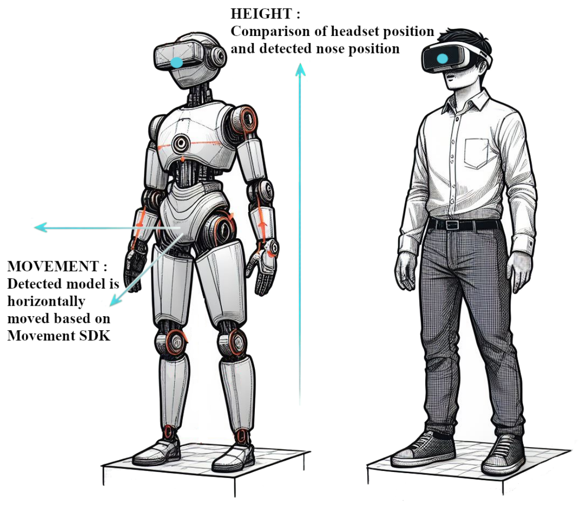

Figure 3.4: Sketch of the continuous position and movement calculation

3.4 Legs visualizations

Initially, right after the detected landmarks were received, they were projected into the VR as a set of disconnected points as seen in the figure 3.3. However, for the VR experience this was not ideal, as this type of visualization does not create the illusion of self-embodiment. Therefore, 4 different visualizations were proposed and are further described below.

Full avatar

The leg tracking visualisation that would be closest to the reality is to show a 3-dimensional representation of the user's whole body. This virtual body is referred to as an *avatar* and is widely used in the world of virtual reality.

Figure 3.5: Model of the avatar and the first person view in virtual reality

Footprints

Another proposed solution was to use a 2-dimensional representation of footprints. This would get rid of any occlusion problems that could occur when using full body avatar visualisation. However, this representation loses information about vertical position of the foot in space. To add this information additional visual channels - colour and transparency - were used.

The primary conveyed information is whether the user's foot is placed firmly on the ground or not. This is done by colour change, where green colour represents position on the ground and blue colour represents raised foot. The other important information that should be conveyed is the foot distance from the ground. This is done by linear change in transparency of the blue colour, where virtual footprint of highly elevated foot should be less visible than footprint of foot closer to the ground.

Figure 3.6: Model of the footprints and the first person view in virtual reality. Right foot is slightly raised in the real world.

3D shoes

The concept of 3D shoes came from the combination of previously mentioned visualisations. The idea behind this representation was to come up with a 3-dimensional visualisation solution, that would not need any additional visual channel for vertical position and would not suffer the problems of large self-occlusion.

In terms of implementing this solution, the same avatar was used as in the first visualisation, but the virtual body from the ankles up was rendered as invisible.

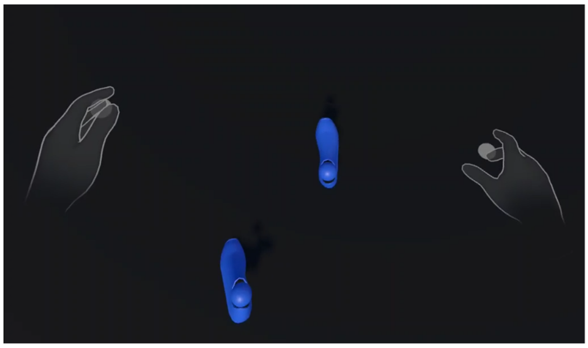

Figure 3.7: Model of the 3D shoes and the first person view in virtual reality

No visualisation

Last approach was to not use any visualization at all. In this case user has no information about leg positions in the virtual world and the only visual feedback is the position of their hands due to enabled hand tracking during the whole VR experience.

This approach was an important part of the subsequent testing process because the results can be used as a control measurement for the comparison with the other visualization techniques. This can help answer the question about the importance of leg tracking in the VR walking experience.

Chapter 4

Prototype evaluation

This chapter describes the preparation and testing process of the prototype leg tracking solution. It begins by outlining the basic research questions and testing objectives. This is followed by the description of test design and at the end of this chapter is a summary of the testing results and a discussion of the implications for future therapeutic application development.

4.1 Research questions and goals

At the beginning of any research or thesis, there should be proper research questions and goals defined. The UX Research book[35] by Brad Nunnally and David Farkas states that a clear definition helps to focus on the central issue to be resolved and can guide the whole work process. Below is a summary of the main goals and questions I tried to answer during the user testing.

1. In the virtual world, can a person recognize where they are stepping?
2. Is the ability to detect where a person is stepping affected by the added information from leg tracking?
3. Is walking with enabled tracking more accurate than without it?
4. Which visualisation allows the most pleasant experience?
5. Explore the overall experience of walking in VR with and without leg tracking.

4.2 Test design

There are many factors that can affect the test results, therefore the test design needs to be carefully thought out before conducting any testing. This chapter will discuss the course of testing as well as the different design decisions made prior testing.

4.2.1 Course of testing

During each test, participants were following a predefined testing path, shown in figure 4.1, several times. Two rounds of testing were conducted for each visualisation technique, where leg tracking was visualized.

During the first series of walkthroughs, participants were asked to walk along a path so that the detected feet matched the virtual path as closely as possible. This approach was used primarily to evaluate the accuracy, however, it also brought an insight into how people perceive their position in the real world in comparison to the virtual world.

Second series of passes focused on participants subjective experience and the ability to immerse with VR world. Participants were asked to follow the path, but this time they were instructed to walk the path as they think they would be the most accurate in the real world. They were asked to use the tracking information according to their own devising.

To evaluate the user experience during the walkthroughs and to gather information for comparing individual visualizations, an ongoing conversation was held with the participant. Furthermore, after completing the walkthroughs, a quick final survey was administered to gather additional feedback.

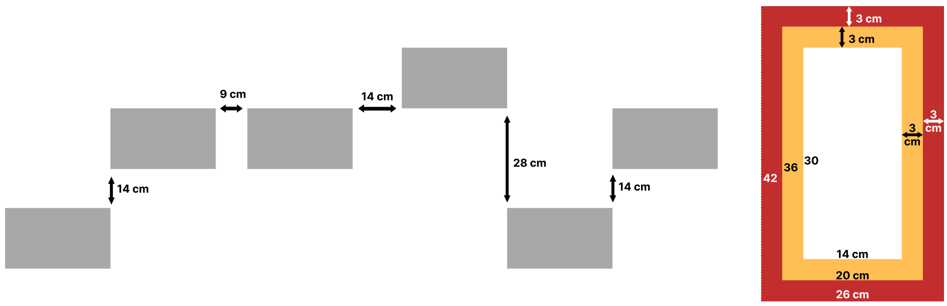

Figure 4.1: Schema of the optimal test path *(on theleft)* and the enlarged testing step area with three regions used for accuracy measurement *(on the right)*

4.2.2 Testing environment

During the testing process, there was an effort to obtain some measurable data representing the accuracy of the leg tracking solution. It was decided to use a path where each step is marked as a predefined rectangular area with three regions. The proportions of these areas as well as the scheme of the path passage are displayed in figure 4.1.

This setup then needed to be reflected in a virtual environment, which would not distract the participants. Therefore, a basic virtual room with fireplace and city view, based on a scene from Unity learn[36], was build and used for testing. In the virtual scene, the user only saw the white rectangles indicating the optimal passage.

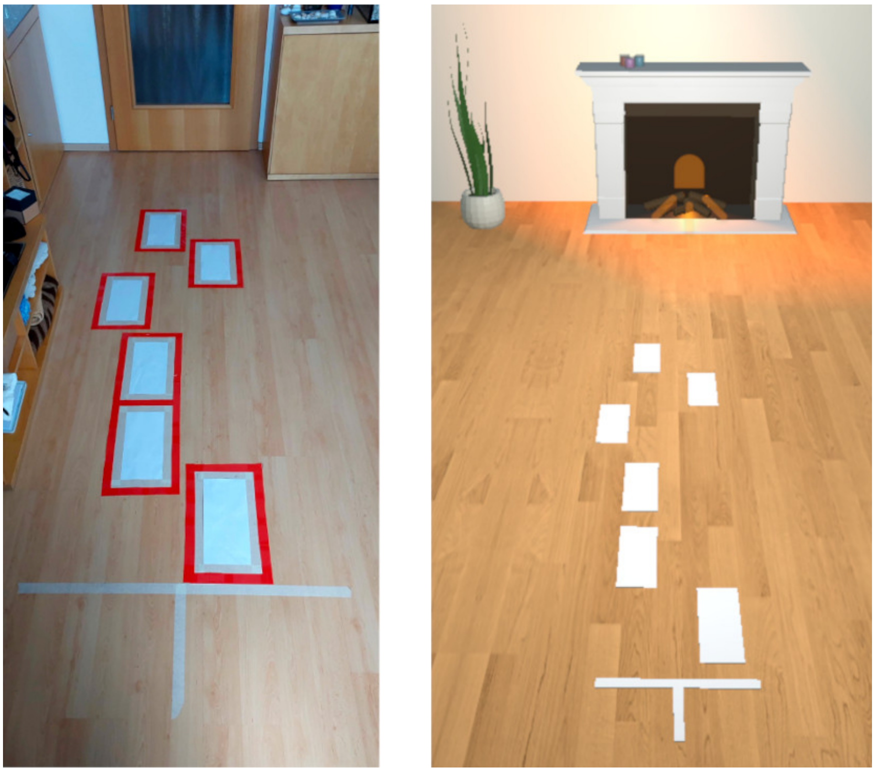

Figure 4.2: Comparison of the testing path in the real world *(on the left)* and in the virtual environment *(on the right)*

4.2.3 Target group

Even though the final therapeutic application is meant for the elderly, during this testing the focus was more on the general experience of walking in VR. For this reason, the target group was not specifically focused on the elderly, rather on the general public.

However, one of the important aspects of the test participants was the size of the foot. According to the initial screener questionnaire, that participants filled out before the testing, it was found out that the foot sizes ranged from EU size 41 to 45, which is roughly from 25 to 28 centimetres. As silly as it might seem, this was an important information as based on that, the area of the test rectangle was set to 30 centimetres.

4.2.4 Possible biases and challenges

Before conducting any testing, it is also necessary to think about the possible challenges and biases. In this project, three main issues were noted before the testing was carried out.

Position of the tracking device

An important issue to be addressed is the position of the tracking device. Even though the MediaPipe application outputs 3-dimensional positions of detected landmarks, it exhibited some limitations in terms of depth recognition. This is not surprising as the positions are recognized from a video stream captured by a single camera. Due to the image being 2-dimensional, the depth information is lost, making it challenging to estimate the correct 3-dimensional position[37].

However, for the purpose of the exercise on sensorimotor walkway, the user will walk in one direction only. Therefore, if the camera is placed perpendicular to the direction of walking, the importance of the depth information should be reduced.

Lighting conditions

Another problem to watch out for are the light conditions while testing. Optical tracking relies upon a visual information, which is most commonly gained from a video camera that acts as an electronic eye[38]. Therefore, it is crucial to have a clear view of the tracked subject in the video. Moreover, it is possible, that the lighting conditions will have a large impact on the quality of the detection. For example, during development it was found that common phenomena such as shadows can confuse the detection algorithm used in MediaPipe.

Testing path

Last thing to watch out for is the shape of the test path. During preliminary testing a symmetrical straight path was used for the walk. However, it turned out that the straight symmetrical shape of the path made it easier for participants to tell, whether they have strayed from the path. Due to this, an asymmetric path, as seen in the figure 4.1, was used in the consequent testing.

4.3 Testing results

Five participants were asked to test the leg tracking solution, from which three were men and two women. Participants ranged in age from 16 to 28 years and four of the participants had some previous minor experience with VR. This section provides an overview of the results of the testing conducted with these participants.

4.3.1 Accuracy

During the testing, the accuracy without leg position visualisation turned out to not be as big of a problem as initially expected. In general, none of the participants walked completely accurately, but they never stepped entirely out of the red rectangular area.

Participants were the most accurate while walking without any visualisation. All of the visualisations using MediaPipe supplied data had very similar results, but the footprint visualisation proved to be the most accurate by a small margin.

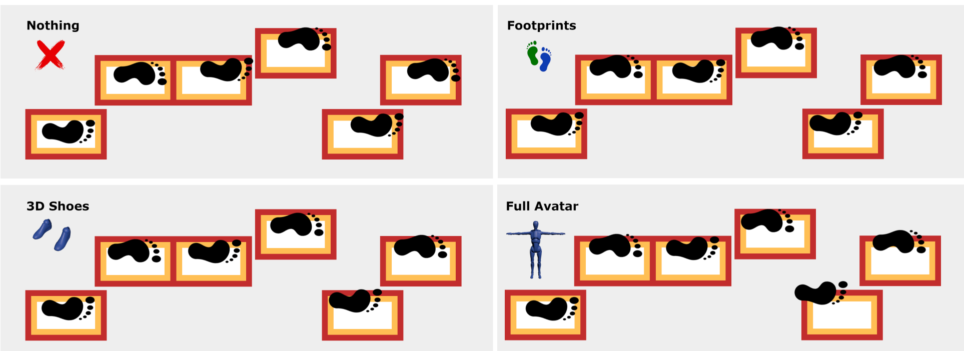

Figure 4.3: Illustration of the walkthrough of one of the participants

4.3.2 Participants feedback

When looking at the measured data, the accuracy seems promising. However, the user experience is completely different topic. Even though the participants were most accurate while walking without any visual feedback, all of them agreed, that some kind of visual feedback might provide a better user experience in the form of easier walk. This claim was also supported by the fact that the time taken to pass through the test walkway was significantly shorter when using visual feedback.

Out of the MediaPipe tracking visualisations, the footprints were the most accurate, however most of the participants concluded that the 3D shoes visualisation was more comfortable. This was mainly because of the 3-dimensional nature of the visualisation, that provided additional intuitive feedback.

4.3.3 Encountered problems

During testing, issues that were not foreseen at the beginning occurred. Some of them are minor and could be easily fixed, but some have proven to be very serious and make it almost impossible to use the proposed solution in the future application.

Tracking accuracy

One of the crucial issues with the MediaPipe tracking solution is that sometimes it had a problem distinguishing left and right leg, causing them to swap places in the virtual environment. Another problem arose from the incorrect depth detection. That impacted the position of user's feet, which pointed in an incorrect direction almost the entire time. Lastly, the detection refresh rate combined with imprecise detection caused the visualisation to jump around.

Device used for the MediaPipe application

At the beginning of the development phase a Samsung S10e smartphone was used for landmark detection. The latency of landmark detection was around 130 milliseconds, which, added to the delay in transferring and rendering the information in VR world, caused an unpleasant feeling for the participants. This problem was partially resolved by using a more powerful device for landmark detection, specifically a Samsung S22 smartphone was used in later testing.

Need of large open space

Another problem encountered during preparation of the testing scene was that the camera's field of view is quite small. This results in a need of a large space for the detection. For example, length of the testing path was slightly over two meters and the camera detecting the landmarks had to be almost four meters away in order to record the whole testing scene. And it comes without saying, that the whole space in front of the camera must be clear to avoid any occlusion.

Possible detection of one person only

One of the most serious issues found during the testing phase was that MediaPipe landmark detection application works only if there is exactly one person on the captured video. Even if the detection of one person was perfect, this problem made the proposed solution impossible to use for the developed therapeutic application, as the therapist has to stay close to the patient in case of a fall, nausea or any other complication.

4.4 Conslusion

Based on the conducted testing, it was found that the visual feedback has many advantages, however, it seems to not be as important as was initially assumed. The participants were able to walk accurately even without any visual feedback, although they seemed to be less confident and needed more time to walk through the test walkway.

Even though the test results showed a good enough accuracy while walking through the test walkway, the data provided by MediaPipe proved to be unreliable, due to many issues described in previous section. These issues deteriorated the overall user experience and caused problems for the participants.

In conclusion, the gathered information showed, that not having leg visualisation did not cause any significant issues to the participants. Based on that, in the following work the focus was shifted to the therapeutic application development instead of leg tracking.

Chapter 5

PhysioBridge design

After collecting the feedback from the leg tracking prototype testing, the next step was to design the therapeutic application later called as PhysioBridge. This application is intended for use at the Nová Slunečnice retirement home, where patients regularly participate in sensorimotor training on the sensorimotor walkway. Although, the use of this application is not limited only to this specific retirement home, the sensorimotor walkway is not commonly used exercise and thus the design decisions were based solely on the needs of therapists and patients from Nová Slunečnice.

This chapter describes the target user groups of the PhysioBridge application, followed by the key requirements and the proposed application design.

5.1 Target user groups

The PhysioBridge application consists of two distinct applications, each intended for different users. The target group for the VR application are the patients performing the sensorimotor exercise. The target user for the control application is the physiotherapist who is leading the training session.

- **Patient**: an elderly person roughly around 80 years old. Minor issues with mobility are expected, but it is assumed that the patient can still walk. No or minimal technical knowledge and experience with virtual reality is anticipated.

- **Physiotherapist**: a professional staff member leading the sensorimotor training. Some basic experience with using Android mobile applications and virtual reality headsets is expected.

5.2 System requirements

Before starting the development of any application, it is a good practice to create a list of requirements that can be used to evaluate the completeness of the solution. This section describes the functional and non-functional requirements for the whole system, including the VR experience and the control application.

5.2.1 Functional requirements

1. The system should provide a complex VR experience to the sensorimotor walkway exercise
2. The user should be able to set the real world position of the walkway in the VR experience
3. The system should provide multiple pleasant, colourful VR environments
4. The system should allow the physiotherapist to scale the complexity level of the exercise
5. The system should enable the physiotherapist to control and monitor the experience through a control application
6. The control application should be able to show the current state of the VR experience
7. The control application should provide multiple spectator views
8. The system should be able to provide user movement data to the VR Dashboard[39] application for progress tracking

5.2.2 Non-functional requirements

1. VR application should run on the Oculus Quest system
2. Control application should run on an Android smartphone, with Android version 10 or higher
3. The user interface should be available in the Czech language
4. The user interface should be as simple as possible

5.3 UI design

PhysioBridge application is not the first VR experience utilized for proprioceptive training at the Nová Slunečnice retirement home. In fact, PhysioTrails has been in use since 2021. PhysioTrails[40] is a virtual reality application developed as a bachelor thesis by Markéta Machová. It is specifically designed for proprioceptive training on a balance platform called Posturomed and has become quite popular among the elderly after its incorporation into the training sessions.

The overall design of the PhysioBridge application discussed in this thesis is significantly inspired by PhysioTrails. This is primarily because both applications are developed for the same retirement home and are intended for use during the same training sessions. According to Jakob Nielsen and Megan Chan and their theory on Mental Models[41], when creating new designs, it is helpful to draw on familiar mental models. For this reason, I have decided to make the UI of the VR experience as well as the control application similar to PhysioTrails. Moreover, there are plans for future integration of these applications to enable continuous training without the need for app switching and similar UI will allow for easier integration.

VR application

Both PhysioTrails and PhysioBridge are developed for a different kind of exercise and thus they provide a different kind of VR experience. However, PhysioTrails application still served as an inspiration. In particular its calibration process, shown in the figure 5.1, has served as the basis for the VR Lobby scene of the PhysioBridge application.

Figure 5.1: User interface of the PhysioTrails VR[40] application calibration process

Control application

The overall design aims to maintain the original aesthetic of the PhysioTrails Mobile UI illustrated in figure 5.2. However, due to both applications providing slightly different options, there was a need for some minor changes. For example, this includes the different settings or options in the spectator screen.

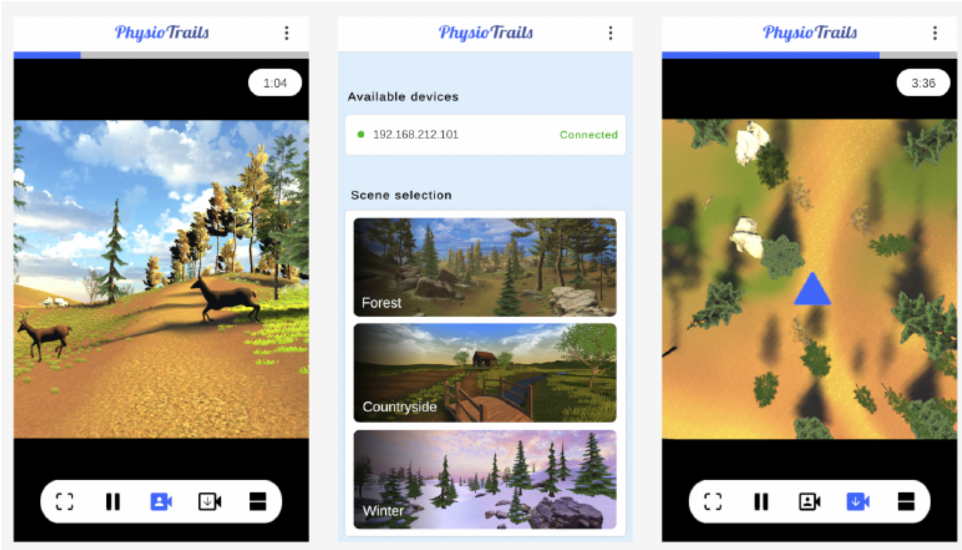

Figure 5.2: User interface of the PhysioTrails[40] control application

5.4 Calibration

To fulfill the requirement number 2, the system should enable creation of a link between the physical sensorimotor walkway and its virtual version. A 3-dimensional model of a sensorimotor walkway was designed to mirror the dimensions of the actual walkway. However, in order to ensure the accuracy of the link between the real and the virtual walkway, there is a need for a calibration process.

PhysioTrails, which served as an inspiration for PhysioBridge application, also implements a calibration process. During the calibration, user is asked to indicate the left and right handles of the Posturomed platform using a pinch gesture. Subsequently, a cart model is generated, positioned, and rotated based on the input data. While this approach is simple and straightforward, it must be repeated each time the application is launched. Moreover, the calibration process is performed in the virtual environment and therefore the user does not see the position of the platform, making the calibration less precise.

During the Meta Connect[42] conference in 2021, Meta announced the

Presence Platform, which provides numerous features empowering developers to build more immersive mixed reality experiences. Among these innovations is the capability for developers to generate world-locked frames of reference known as Spatial Anchors. Users can create an anchor with precise real world position and orientation, which can be later used to drive the transform of a virtual content. These anchors are stored either locally on the user's headset or in a cloud repository, both however enables for later loading of the anchors even when the application is repeatedly launched.

This approach of utilizing Spatial Anchors has the potential to simplify the overall calibration process and improve the user experience, as the calibration would be required only once after the first launch of the application. Naturally, this holds true only under the assumption that the sensorimotor walkway will not be moved around in real life and the same headset will be used during the training sessions.

5.5 Complexity

A part of the thesis assignment and the software requirements (requirement number 4) was to design a mechanism for scaling the complexity level of the exercise. To come up with ideas how to fulfill this requirement, it is necessary to consider how the exercise will proceed and identify the aspects that can be controlled by the application design.

The course of the exercise is fairly straightforward. During the VR experience, patient walks on a virtual representation of the sensorimotor walkway. This being said, the parameters that can be manipulated are either the virtual environment or the appearance of the virtual representation of the sensorimotor walkway. The suggested approaches, based on these two aspects, will be described below.

5.5.1 Environment based approach

The virtual reality has the potential to affect individual's emotional and cognitive states. The visual presentation of the virtual environment, being significant part of the VR experience, holds the similar potential.

The concept behind the environment based approach is that introducing somewhat unpleasant surrounding in the VR experience could influence the complexity level of the exercise. However, it is important to emphasize that the primary goal remains for users to enjoy the VR experience. Therefore, any extremes should be avoided in the environment design.

Ultimately, two different environments were designed, with one intended to offer a more pleasant experience, while the other was intended to evoke a slight sense of uneasiness. The primary concept behind designing the less pleasant environment was to elevate the bridge, therefore provoking a sensation of mild discomfort. Furthermore, the overall look of the scene should be more hostile than the first scene.

The first, more pleasurable environment, was designed to depict a *Countryside* landscape, with running water under the virtual bridge and familiar animals running around. The second environment was designed as a *Desert*, which in itself evoke a sense of hostility. The virtual bridge will be placed on a stone rock over a desert village.

Another idea proposed during the initial design phase involved incorporating sudden loud noises, such as the sound of falling rocks behind the patient in the Desert environment. However, this could increase the risk of sudden movement injury if the patient gets startled.

5.5.2 Walkway based approach

The sensorimotor walkway is fundamentally a medical parallel bars system with different materials on it. It was decided to visualize it in the form of a bridge, which can be further modified to add another layer of complexity to the exercise. Since the sensorimotor walkway also contains variety of different carpets and materials, this was also included as an aspect that could be modified.

Before proceeding with the proposed solutions, it is crucial to highlight the primary objective of the sensorimotor walkway exercise as it is closely related to the design decisions described below. Patient's goal is to enhance sensory perception by engaging with the various materials on the sensorimotor walkway and thus stimulate the neurons in their feet. Given that vision is our primary sense[43], what we see in the virtual reality can influence our perception and thus increase the complexity of the exercise.

Considering all of the above-mentioned factors during the designing process, the following modifications were proposed.

Missing planks

By conceptualizing the bridge as a wooden structure with planks, there is an option to remove certain planks, provoking a fear of falling and thus potentially causing an increase in the exercise complexity. Consequently, users may instinctively avoid looking downwards, focusing instead on the materials they are feeling rather than on their steps. This redirection of attention aligns with the exercise objectives, potentially furthermore enhancing the effectiveness of the exercise.

Missing handrails

Similar to the missing planks, the bridge handrails can be removed. It may be a case of removing only one of the handrails or both for even greater complexity. This removal of handrails is supposed to create the illusion of a support system loss, potentially impacting walking complexity. In reality, the handrails would naturally remain intact to offer essential support to the patient as needed.

Carpets alteration

Another approach to increase complexity involves altering the visual appearance of the carpets within the virtual environment. This could be achieved through subtle modifications of the materials or by rearranging the positions of the carpets. Another idea would be to remove one or more carpets and let patients rely solely on their senses in order to recognize the material.

These customizations of the carpets could also serve as a means to introduce gamification elements into the VR experience, presenting challenges for the patient. For instance, one carpet could be modified, and the patient would be tasked with identifying the altered one. This could in return increase the attractiveness of the exercise.

Chapter 6

Implementation

This chapter discusses the implementation of the PhysioBridge application. It starts by briefly presenting the technologies used during the development and follows up with the description of the implementation process of both the VR and the control applications as well as some key challenges encountered during the development.

6.1 Technology stack

Despite the VR experience being developed for the Meta Quest standalone platform and the control application designed for mobile Android devices, both applications were developed as a single project using the Unity engine. This engine was chosen for its popularity in the game industry, meaning there are many resources available, be it assets, tutorials or troubleshooting discussions.

To create custom-made 3D models, software tools including Autodesk Maya and Substance Painter were used. This section briefly presents an overview of the technologies used in the development of both the VR and control application.

- **Unity engine** is one of the world's leading platforms for game development. Unity allows developers to create 2D, 3D, augmented reality, and virtual reality experiences across various platforms like PC, mobile, consoles or web. The engine provides users with an intuitive editor for building game scenes and supports scripting with the C# programming language. Furthermore, Unity provides the opportunity to utilize Unity packages, offering a wide range of assets and pre-made solutions in the Unity Asset Store.

- **Autodesk Maya** is a professional 3D computer graphics software used primarily for modelling, animating, and rendering 3D scenes and characters. It is widely used in industries such as gaming and cinematography. In this thesis it was used for the creation of the custom-made models, including the 3D model of the virtual bridge along with the variety of different carpets as well as other models used in the VR experience.
- **Substance Painter** is a 3D painting software offering a range of tools for creating high-quality textures and materials for 3D models. It offers the option to create custom-made textures through direct painting on a 3D model as well as a solid base of already pre-made textures. Furthermore, Substance Painter offers the ability to export textures in a variety of templates, including those specifically designed for Unity.

6.1.1 Unity packages

Package name	**Package usage**
Meta XR All-in-One SDK	A wrapper package with the Meta SDKs for VR development
Bézier Path Creator	Editor for creating paths used for animals movement
Mirror	Networking library for Unity used for communication between the VR and the control application
AllSky Free	6-sided cubemaps used for scenes creation
Animal pack deluxe	Animals assets used for scenes creation
Animal pack deluxe v2	Animals assets used for scenes creation
LowPoly Environment Pack	Nature assets used for scenes creation
Simple Low Poly Nature Pack	Nature assets used for scenes creation

Table 6.1: Table of utilized Unity packages and their application

6.2 VR application

This section presents the virtual reality part of the PhysioBridge application. It can be run in a standalone mode and it tries to use the latest technologies available in the Oculus headset in order to provide a better user experience. In this section, an overview of the most crucial parts of the VR application implementation is provided.

6.2.1 Hand tracking

Interacting with the virtual environment is a key aspect of any VR experience and therefore it should be one of the initial topics addressed. In recent years, there has been a significant advancement in the hand-tracking technology, and controllers are no longer the only means to mediate interactions in virtual reality. This is particularly beneficial for the PhysioBridge application as patients need to keep their hands free during the exercise in case they need to grasp the walkway railings. Therefore, it is only natural to use hand tracking as the primary mode of interaction in this VR application.

To enable hand interactions, the Interaction SDK was utilized. This library offers numerous features supporting the interactions for both controllers and hands in VR experiences. One of the provided features enables developers to define custom hand gestures, that can later be recognized by the system. The PhysioBridge VR experience currently supports three gestures for interaction with the virtual environment.

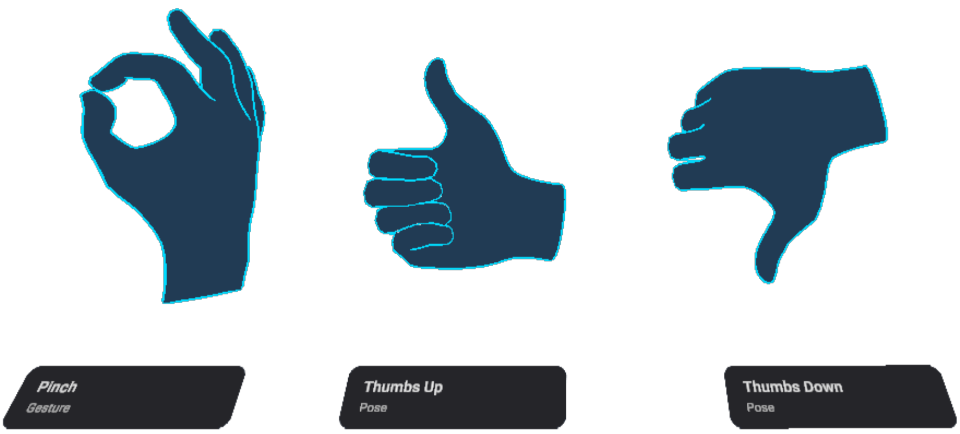

Figure 6.1: Illustration of hand gestures supported in the PhysioBridge application

- **Pinch** gesture is commonly used as the standard trigger action in the Meta Quest headsets. In the PhysioBridge application this gesture is used to select UI elements as well as to indicate the position of the anchor during the calibration process.
- **Thumbs up** gesture is used during the calibration to indicate the end of the calibration process.
- **Thumbs down** gesture can be used to return to the virtual lobby from the exercise scene. The second purpose of this gesture is to remove stored spatial anchors from local storage during the calibration process. This action is primarily intended for debugging purposes and it is not expected to be widely used during the training sessions.

6.2.2 Sensorimotor bridge

The virtual representation of the sensorimotor walkway plays a key role in the entire virtual reality experience. As described in the design chapter 5.5.2, the decision was made to implement the virtual walkway as a customizable wooden bridge with planks.

During consultations at the retirement home, the sensorimotor walkway and all the carpets were measured to ensure the models match the real world dimensions. Furthermore, all models were optimized to minimize polygon count in order to increase the overall performance of the VR application.

Figure 6.2: Comparison of the sensorimotor walkway from the Nová Slunečnice retirement home and its virtual representation

The most significant difference between the sensorimotor walkway and its virtual representation, depicted in figure 6.2, is a small wooden gate situated at the end of the virtual bridge. This addition was requested by the physiotherapist after a preliminary testing. During immersion in the virtual reality experience, patients may feel inclined to continue walking through the environment. However, in reality, reaching the end of the walkway leads to either a significant step or sometimes to additional training equipment, posing a risk of injury. The virtual wooden gate serves to prevent patients from unintentionally traversing across the walkway's endpoint.

6.2.3 Calibration

Given the assumption that the sensorimotor walkway is not moved around due to its size and weight, the approach using Spatial Anchors was able to be implemented. A Spatial Anchor[44] is a world-locked frame of reference, that represents a fixed position and orientation in the real world. The PhysioBridge uses the Spatial Anchors feature to position the virtual bridge in accordance with the real sensorimotor walkway.

The whole calibration process is implemented as an augmented reality experience in the Passthrough mode. This is a feature of Oculus headsets, which allows users to momentarily exit the virtual world and to see a real-time view of their surroundings. This gives an opportunity to simplify the task of choosing the appropriate position for the virtual bridge within the real environment.

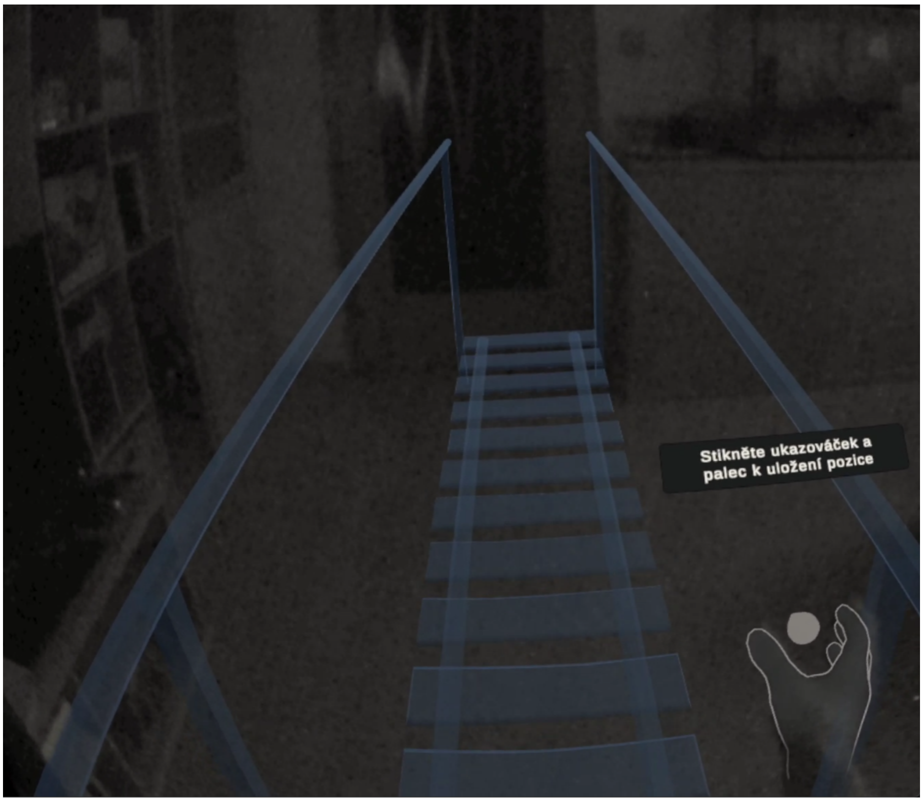

Figure 6.3: The user's view of the calibration process in the virtual experience

Although the calibration process may seem as a distinct scene in the VR experience, it is implemented within the VR Lobby scene. The transition between VR Lobby and calibration is implemented within the *CalibrationManager.cs* script, which, among other minor modifications, changes Skybox and enables the Passthrough mode. This may seem like an additional challenge, especially since the script would be unnecessary if both the lobby and calibration were implemented as separate scenes. However, this approach was not possible due to issues with Network synchronization in the Mirror library. This issue is discussed in more depth in the challenges section (viz. 6.4.3).

The calibration process can be entered from the VR Lobby through a button in the UI menu. To return from the calibration to the VR Lobby, a thumbs up gesture has to be recognized by the system. The calibration process itself involves two modes, anchor creation and anchor selection, described below.

Creation mode

This mode is activated when no spatial anchor can be loaded. This happens either when there is no information about the anchor stored in the user's headset, or when the stored anchor position is at a significant distance.

During creation mode, user is presented with a transparent preview model of the virtual bridge, which is attached to their hand. This enables the user to manipulate the virtual bridge by moving and rotating their hand. The movement and rotation of the bridge mirrors the transformations of Raycaster Pinch Visual object implemented internally in Meta XR Core SDK. However, the preview model of the bridge is restricted to rotation around the Y axis. This limitation is possible because the dimensions of the real and the virtual walkways are identical and the walkway is expected to be parallel to the ground.

When user makes the pinch gesture with their hand, the current transformation of the bridge preview is stored as a Spatial Anchor in the headset. The creation mode is subsequently switched to the selection mode.

Selection mode

In contrast to the creation mode, the selection mode is activated whenever a spatial anchor can be loaded. A preview model of the virtual bridge is spawned with the transformations corresponding to the stored anchor.

Selection of the virtual bridge is implemented similarly to an interaction with any standard UI element. Upon hovering over the preview, it is highlighted, and using the pinch gesture, the bridge can be selected. Upon selection, the stored Spatial Anchor is removed from the local storage and the mode switches back to the creation mode.

6.2.4 Environmental scenes

According to the thesis assignment as well as the requirement number 4, the VR experience should provide a pleasant, colourful virtual environment. As noted in the design section 5.5.1, two distinct environments were designed and developed within the PhysioBridge application.

To minimize the polygon count, both scenes were stylized using a low-poly art style. Despite Unity offering the Terrain tools package for creating detailed terrains, all models in this VR application (including terrains) were either custom-made or obtained from the Unity Asset store to preserve the low-poly look.

Figure 6.4: View of the countryside scene

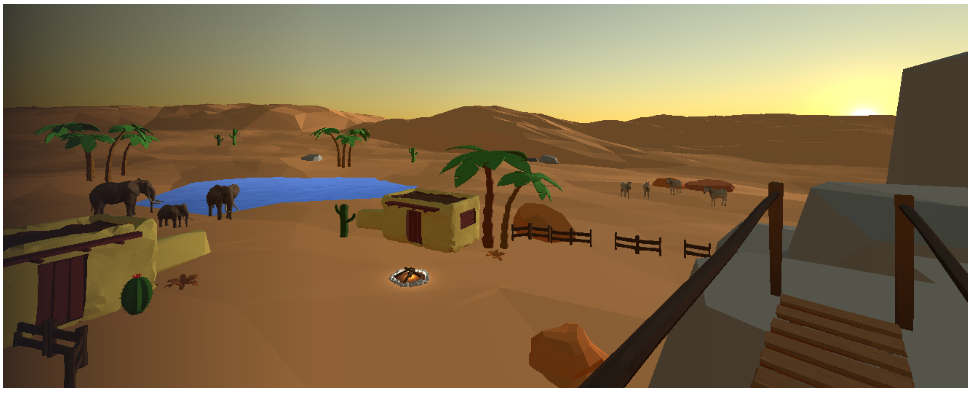

Figure 6.5: View of the desert scene

Dynamic elements

The animated objects play a key part of the virtual environments, as they make the virtual experience dynamic and more interesting. In the implemented application, the *Animal pack deluxe* and *Animal pack deluxe v2* packages from Unity Asset store were used to bring some movement into the VR experience. These packages contain numerous models of animated and rigged animals, ready to be used in the Unity editor.

Despite the animations being available within the package, there is still a need for the implementation of the animal movements. This was done using the *Bezier Path Creator* package, which allows creation of smooth paths within the Unity editor. Objects can be subsequently moved along the predefined paths.

Randomized scripts

The VR experience of walking on a sensorimotor walkway takes place in a relatively small space, encompassing both physical reality and virtual world. While this has the advantage of eliminating the necessity for constructing large virtual environment, it also has its limitations. The use of a relatively small virtual world can cause users to quickly recognize the scripted nature of the virtual objects placed in the scene.

To address this challenge, randomized scenarios for some of the animals were implemented. The animation transitions are driven by a continuously updated random parameter. Each virtual experience is thus slightly different, due to the subtle variations in the animated objects.

Sounds

While visual appearance is typically the first aspect considered when describing the virtual environment, audio also plays a crucial role. In total, 9 different sounds were downloaded from free resources such as Mixkit, Quicksounds and Pixabay. These audio components include sounds that introduce elements of the environment, such as running water, fire cracking, animal noises, and ambient background sounds, enhancing the overall immersion.

6.3 Control application

To fulfill the requirement number 5, a control application for Android smartphone had to be created. One of the most difficult challenges to tackle during implementation was the communication between the control application and the VR device. In this section, this challenge, along with the UI implementation and linking the application to VR Dashboard will be described.

6.3.1 Networking

For network communication it is common to use ready-made libraries. One of such is Mirror, which was previously mentioned in the prototype chapter 3.2. It is a high-level Networking library made specifically for the Unity engine. This library allows for object synchronization, including the transformation and any variables in a script, while providing the capability to automatically trigger a function upon any change.

The VR application acts as a host, which means that it is running a server and a local client at the same time, while the control application is client only. The server is then responsible for the synchronization of any data to all of the connected clients. The data include various information, such as the state of the VR world or the VR headset position.

As the server has the authority over all the synchronized data, to modify it, the client needs to send a command to the server. In other words, any change made locally to the data will not be reflected on other clients unless the server command is sent.

6.3.2 User interface

The user interface of the control application was created in Unity using components of the Unity User Interface toolkit. The overall user interface of the control application is inspired by the design of PhysioTrails, however the design had to be slightly modified. This is due to the different nature of the exercises. The only brand new screen present in the PhysioBridge application is the sensorimotor walkway settings screen.

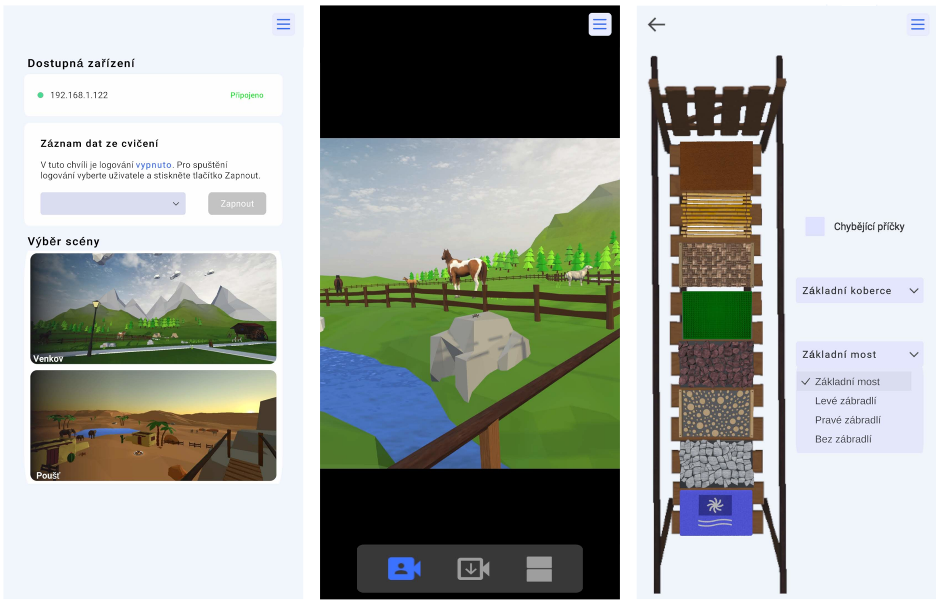

Figure 6.6: User interface of the PhysioBridge control application

Bridge settings

Even though the bridge settings screen provides all of the options described in the design section 5.5.2, it can still be considered a prototype. As the options are currently limited and their importance is not yet validated, the focus was put on implementation simplicity. Therefore, the bridge preview in the control application is implemented through switching sprites. In the future it would be better suited to display a preview of the real game object.

Whenever a change of settings is made, updated values are synchronized with the VR application to provide a real time preview in the virtual environment. The virtual bridge is implemented in a modular way, where the specific parts can be hidden or moved accordingly. This allows for a single bridge model to be used.

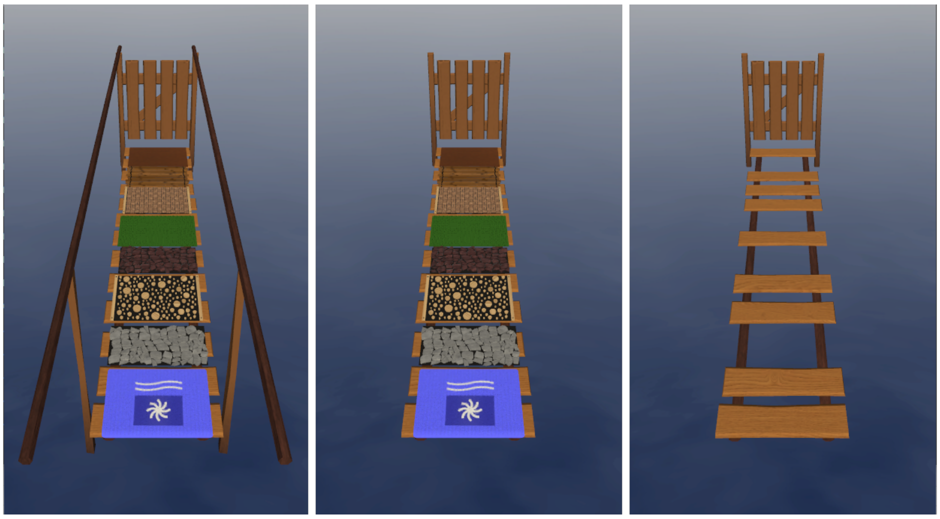

Figure 6.7: Example of different virtual bridge modifications

Spectator mode

Another requirement for the control application is to provide multiple spectator views. Currently, the application supports three different options to observe the VR experience - first person view, top view and multi view, which combines the two previous options.

Even though video streaming seems to be the obvious choice for spectator mode implementation, this approach places additional demands on the performance of the VR device as well as the network, making this approach unusable.

Ultimately, only the headset transformation is synchronized to the control application. There a replica of the virtual world with additional spectator cameras is rendered. The first person spectator camera is positioned according to the synchronized transformation of the headset. Based on the spectator mode, either the first person or the static top view camera is rendered accordingly. For the multi view both cameras are used.

Due to randomization of the animal behaviour, it is necessary to also synchronize the random seed. As the virtual environment is running on different devices, without the seed synchronization, the environments would behave differently.

6.3.3 VR Dashboard

Part of the thesis assignment, addressed in requirement number 8, was to link the PhysioBridge application to the VR Dashboard[39], which an application developed as a master's thesis by Leoš Řeháček. This application provides a way to collect and analyze data from VR training applications through the

VRLogger Unity package. This package was integrated into the PhysioBridge application and used for collection of the position and rotation data of the VR headset and hands. The tracking is enabled once the virtual environment for the exercise is loaded and ends when the patient returns back to VR Lobby.

Alongside the user's transformation data, essential details regarding the chosen environment and settings are logged. Additionally, events of user grabbing and releasing bridge railings are logged during the course of the exercise. As the position of the virtual railings corresponds with the real world position, detection of these events is implemented through collision of virtual bridge railings with the GripPoint collider on the virtual hands.

Figure 6.8: Example of line charts from VR Dashboard depicting the course of the exercise walkthrough

6.4 Challenges

Facing different kinds of challenges is common in any development process. This section will briefly describe the most severe encountered issues.

6.4.1 World state synchronization

In the first versions of the control application a feature to join an ongoing VR experience was implemented. Upon testing it was observed that the spectator view did not match the virtual experience. This is caused due to the approach used to implement the spectator mode.

The virtual environment is dynamic and its state is dependent on the random seed and the time elapsed from the start of the scene. This might sound trivial at first, but even if the seed and time elapsed were synchronized, it would be hard to recreate the actions that have led for the environment to be in the given state.

The possible solution would be to control the whole virtual environment through the server, so that all the clients would be synchronized. To implement this approach, it would be necessary to re-implement the whole logic running the dynamic actions inside the environment. Due to this issue being discovered late in the development, it was decided to remove the ability to join an ongoing exercise session with the option to re-implement it in the future.

6.4.2 Disappearing spatial anchors

This challenge was originally discovered when conducting the first presentation of the PhysioBridge application at the retirement home. When starting the calibration process the virtual bridge appeared below the floor level and could not be selected nor moved.

This behaviour was caused by improper anchor loading. The Quest headset handles the loading of the anchors internally, based on a provided list of IDs. However, it might not always be possible to locate the stored spatial anchors, most commonly caused by the headset being moved to a different location. This does not trigger any warning in the debug console, as it is expected behaviour when various spatial anchors are stored in multiple locations.

The issue was in the implemented logic, which checked the existence of anchor by the stored anchor ID instead of the loaded game object.[1] This was solved by checking the loaded game object and removing the stored ID from memory when the anchor was not loaded. However, this solution is not optimal as it allows to save only one anchor at a time. It would be more beneficial to extend the implementation to allow storing multiple anchors and it would be a good feature to focus on in the future.

[1] Naturally, the solution was tested in different places prior to the presentation. However, on those occasions the spatial anchor ID was not present in the memory, thus this issue was not encountered.

6.4.3 Calibration as separate scene

The spatial anchors are a great enhancement in the sense of not having to calibrate the application after every launch. Ironically, this caused this issue to be discovered very late in the development as it only appeared during the calibration process.

Originally, the calibration and the VR Lobby were two separate scenes and the only ones that were not loaded additively. Switch between these two scenes caused networking to stop working. After some troubleshooting it was found to be a fairly common problem with the Mirror NetworkManager being replaced on scene load. Different recommended solutions were implemented without much success, so the decision was made to merge the two scenes.

Chapter 7

Testing and evaluation

It is important to note that the purpose of this thesis is not necessarily to develop a ready-to-use application. Instead, it aims to explore the potential of using virtual reality for sensorimotor walkway exercise. However, if the application proves to be usable, it is expected that it will serve as a basis for a future physiotherapeutic application. This applies especially to the control part of the PhysioBridge application. Therefore, it was decided to separate the testing process into two parts.

The first section of this chapter focuses on the usability testing of the control application, as it is crucial to ensure its usability and understanding for both the later research and future physiotherapeutic applications. The second part of the chapter will discuss the testing of the VR experience, with focus on answering research questions related to the potential of using virtual reality for sensorimotor walkway exercises.

7.1 Control application

According to Jakob Nielsen[45], who is widely known in the software usability field, useful application can be defined as an application that meets the utility and usability criteria. Utility means that the application provides features that meet the users' needs. This is assumed to be accomplished as all the requirements specified in 5.2 are implemented. Usability of the software is more focused on how easy and pleasant the implemented features are to use. For this purpose, usability testing is often conducted.

7.1.1 Testing scenario

A testing scenario was prepared ahead of the usability testing. This scenario consists of related tasks, leading the participant through the main functionalities of the control application. The task instructions were phrased in general terms, in order to validate the clarity of the user interface.

It should be noted, that although the focus was on usability testing of the control application, it was not expected to be used without the Oculus headset and the VR part of the application. Therefore, part of the testing process also happened on the VR platform, specifically the virtual bridge calibration.

Before the usability testing, the participants were thoroughly informed about the application purpose as well as the course of the testing. The scenario used for the usability testing of the control application was as follows:

1. **Connect the control application and the VR application**
   - The participant should start both the control and the VR application and then connect to the Oculus headset via the control application interface.
2. **Start the VR experience with logging enabled for Participant 1**
   - The participant should understand from the control application UI, that they have to first go through the calibration process in the VR application. Then the participant should enable logging and start the experience.
   - This was an important task as it focused not only on the control application usability, but on the clarity of the calibration process as well.
3. **Display different views of the VR experience and when ready, end the VR experience**
   - The participant should go through different view options and find the end button in the control application.
4. **Make the VR experience more complex by modifying the virtual bridge settings.**
   - During this task, the participant should locate and modify the bridge settings.
5. **Run the VR application with the modified virtual bridge.**
   - Even though, this may seem like a repeating task, the goal was to follow the participant reaction to the modal window, warning against the disabled logging.

7.1.2 Test participants

The usability testing should be conducted with the end users of the application. For the control application, this means a physiotherapist leading the exercise sessions. However, in the retirement home, there is only one physiotherapist conducting the sensorimotor training sessions which is not enough for proper usability testing. Fortunately, due to the target group not having many requirements, except for some basic experience with using Android applications and virtual reality headsets, it was decided to test with other participants not necessarily from the circle of physiotherapists.

The usability testing was conducted with 5 participants, 3 women and 2 men, including the physiotherapist from the retirement home. The testing was conducted on the Samsung Galaxy M52 5G Android device.

7.1.3 Findings

Ironically, the most significant issue discovered while testing the control application was related to the calibration process in the VR application. The overall design, which requires to use only one hand to determine the position and orientation, proved to not be user-friendly. At the beginning, participants struggled to understand how to manipulate the bridge, leading to a poor user experience. Additionally, it was very difficult to position the virtual bridge accurately with the real sensorimotor walkway. This was mainly due to small hand movements causing large shifts in the bridge position.

In terms of the control application, there were only few minor issues discovered. Especially, when testing with the physiotherapist from then retirement home, who is already used to work with a similar UI from the PhysioTrails application. For the physiotherapist, the only significantly different features in the application were the participants logging option and bridge settings. Both of the new features were used by the physiotherapist without any confusion during the testing.

Among the occasionally mentioned comments were the small size of the buttons and text, which is a minor issue, that was easily fixed after the testing. Other observation made during the testing was that participants expected being able to zoom the spectator view. After discussion with the physiotherapist, it was decided not to prioritize this feature, as it is not something that would be used during the actual exercise. An issue that might be worth solving in the future is that participants tried to exit the VR experience using the Android back button at first. This is a feature they are used to and implementing it might improve the overall user experience.

7.2 VR experience

In comparison to the control application, which focused on the usability testing, the testing of the VR experience was more research oriented. Therefore, this section begins with setting out the research questions and goals, followed by the description of the course of testing and the test participants. The final part presents a summary of the test results and discusses the findings.

7.2.1 Research questions and goals

The importance of clear definition of user questions and goals was already mentioned in 4.1. The main research questions, which I tried to answer by conducting the testing, are summarized below:

1. Does the use of VR increase the attractiveness of the sensorimotor walkway exercise?
2. Does the use of VR have negative effects on the sensorimotor walkway exercise process?
   - This can include various effects such as VR sickness, issues with missing leg tracking, visibility of the virtual world etc.
3. Can VR be used to influence the difficulty of the sensorimotor walkway exercise?
   - This can include methods using psychological elements such as height or missing bridge railings or additional task to recognize the surface with altered visual depiction.

7.2.2 Course of testing

At the beginning of the testing, participants were introduced to the testing process. Subsequently, they did two walkthroughs, both with different difficulty level. After the testing, they were given a short questionnaire focusing on the attractiveness and difficulty of the exercise performed. This questionnaire uses questions with the Likert scale[46], which is a rating scale commonly used to measure opinions, attitudes, or behaviours. Moreover, additional information from a third person perspective were recorded during the walkthroughs.

The first walkthrough was the Countryside scene with a virtual bridge with swapped carpets. The goal was to get the participant familiar with the VR environment and test whether they are capable of recognizing the inaccuracies in the carpets.

The second walkthrough was focusing on the question whether VR can be used to influence the difficulty of the exercise. The Desert scene was used in conjunction with an altered version of the virtual bridge. Specifically, the carpets were hidden and the bridge was missing one railing and some of the wooden planks.

The participants were supposed to perform both of the walkthroughs on the sensorimotor walkway as they normally would without the use of virtual reality. Moreover, they were continuously encouraged to speak about the sensations they perceived from the various surfaces during the whole testing process.

7.2.3 Test participants

The testing took place over the course of a week at the Nová Slunečnice retirement home, spanning four distinct training sessions. A total of seven participants, including four women and three men, participated in the testing process, with ages ranging from 76 to 98 years.

The participants' previous experience with virtual reality and the duration of their ongoing sensorimotor walkway exercises varied among the training groups. This variation ranged from one month to more than two years. It is also important to note that some of the participants had never seen or used a VR device before, which could have affected their perspective on the application.

Age	76	77
Gender	Male	Male
Sensorimotor training	1.5 months	1.5 months
VR experience	One time	None
PhysioTrails experience	One time	None

Table 7.1: Overview of participants from the 1.testing group

Age	85	92
Gender	Female	Male
Sensorimotor training	2 years	1 month
VR experience	2 years	None
PhysioTrails experience	2 years	None

Table 7.2: Overview of participants from the 2.testing group

Age	98
Gender	Female
Sensorimotor training	1.5 years
VR experience	1.5 years
PhysioTrails experience	1.5 years

Table 7.3: Overview of participants from the 3.testing group

Age	92	87
Gender	Female	Female
Sensorimotor training	2.5 years	2.5 years
VR experience	2.5 years	2.5 years
PhysioTrails experience	2.5 years	2.5 years

Table 7.4: Overview of participants from the 4.testing group

7.2.4 Findings

During the course of testing, some unexpected challenges related to the social factor were encountered. I observed a stereotype of an overly polite elderly who only sought conversation without saying anything bad about the VR application. On the other hand, some participants seemed to have some personal issues with others, leading to an unpleasant atmosphere that could potentially impact the test results. Moreover, some participants were very difficult to talk to, both for me and the physiotherapist, during the VR experience as well as the following questionnaire. This was probably either due to the hearing impairment of the participants or their closed personality.

This being noted, the overall findings derived from both the questionnaire responses and the observations made during the exercises are summarized below in sections corresponding to the research goals.

Attractiveness

The overall attractiveness of the exercise enriched by the virtual reality received highly positive ratings. Participants embraced the new approach to the sensorimotor walkway exercise, with some even reminiscing about their youth, particularly while walking in the Countryside environment. However, there's a possibility that this might change over time as the environment is not changing during the experience and may potentially become monotonous after several sessions.

There was only one group, where participants shown a sign of less enthusiasm. According to the participants the environments were too unreal and childish. It is worth noting that this was the testing session previously mentioned with the unpleasant atmosphere caused by bad relations between the participants. Despite this, the participants expressed an interest in trying the application again in the future.

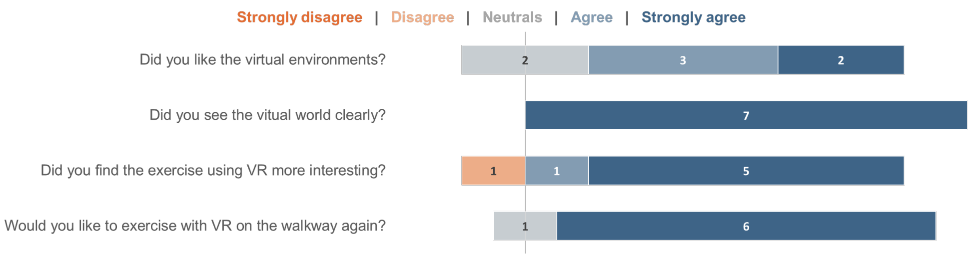

Figure 7.1: Chart showing the results of the *Attractiveness* questionnaire

Negative effects

Another positive outcome of the testing is that no major signs of VR sickness were observed. Only two participants complained of light nausea after completing the VR experience, due to the fear of heights in conjunction with the elevated bridge and missing planks in the second walkthrough.

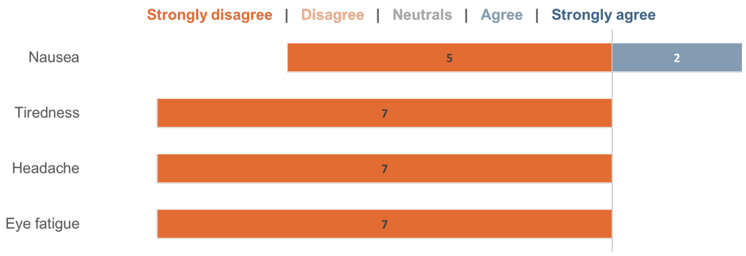

Figure 7.2: Chart showing the results of the *VR sickness* questionnaire

At the same time, the hypothesis proposing that leg tracking is unnecessary was confirmed. The majority of participants navigated the walkway without difficulty despite not being able to see their legs and they were able to determine their position on the bridge. Surprisingly, some participants struggled with recognizing the switched carpets in the first walkthrough. However, it was unclear whether this difficulty actually arose from an inability to recognize the materials or from communication challenges, as many of those participants were difficult to interact with.

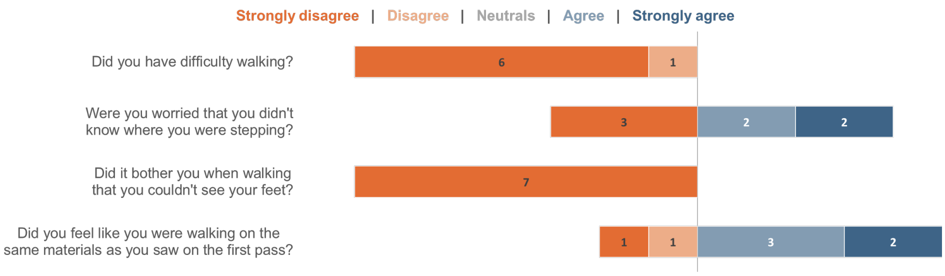

Figure 7.3: Chart showing the results of the *Walking in VR* questionnaire

Level of difficulty

Based on the observations during the second walkthrough, it became apparent that modifications in the environment and bridge appearance can effectively alter the exercise's difficulty level. With the exception of one participant, all individuals showed increased uncertainty in their walking and took longer time to perceive sensations from the carpets.

One of the mechanisms for scaling the difficulty was the elevation of the bridge. Although not apparent from the questionnaire, when observing the participants' walkthroughs it proved to be effective for increasing the complexity of the exercise. Unfortunately, the effects did not align with the exercise's intended purpose. In conjunction with the missing planks, most of the participants were avoiding stepping in the newly appeared gap and thus missed a part of the sensorimotor bridge.

Naturally, not everyone is equally affected by virtual reality and some of the participants were not impacted by the elevated bridge and missing planks at all. One of the participants even stated to be more scared in the first environment, due to the running water under their feet and fear of falling in.

Lastly, the adjustment to the visibility of the railings appears to have the most significant impact on the exercise's difficulty. This was evident during the testing process through observation and was further supported by questionnaire results, where most of the participants agreed that this adjustment increased the difficulty of the exercise.

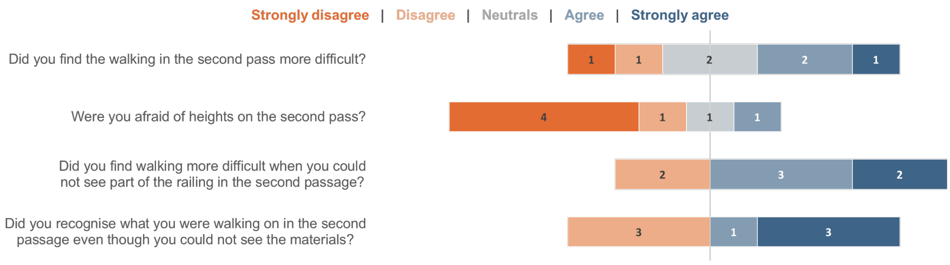

Figure 7.4: Chart showing the results of the *Difficulty level* questionnaire

Additional findings

Two further discoveries were made during the testing phase. The first observation is that the control application is not extensively utilized by the physiotherapist during the exercise. The physiotherapist uses the control application primarily to modify the bridge at the beginning of the exercise and to start the VR experience. However, during the exercise they have to assist the patient in case of any issues while walking, especially with the headset deployed. Therefore, the spectator views proved to be fairly unnecessary.

The second observation is more related to the sensorimotor walkway than to the PhysioBridge application. Currently, the carpets on the walkway are permanently bolted to the walkway base and thus are not regularly changed. Some participants either remembered or believed they remembered the order of the carpets, which influenced the testing process when they were asked to identify the perceived material.

Chapter 8

Future work and study

8.1 Future work

Looking back at the testing process, the developed PhysioBridge application serves as a solid foundation for future studies. It proved to improve the attractiveness of the exercise and did not have any additional negative effects. However, the main issue with the current application is that it distracts the users from perceiving the sensations triggered by the sensorimotor bridge, which is the primary goal of the exercise. Therefore, it is essential to modify the application to better direct users' attention to the perceived sensations. There are different ways to achieve this goal.

The first solution that came to my mind was to implement some kind of timer functionality. However, even if the user followed the instructions and stayed in one place for longer time, there is no way to ensure that the exercise is performed properly. That is, whether the user really tries to feel what they are standing on instead of just looking around for one minute and carrying on. Secondly, during the testing, there were participants who had problems with the feel of some of the carpets as some were for example too sharp and therefore uncomfortable. This means that an option to skip the timer and move on would be necessary.

The second idea would be more complex to implement, but could also have additional benefits such as improved attractiveness. The idea is to add gamification elements to the VR experience, that would require the user to focus on the carpets in order to complete the tasks. An example of such tasks would be to search for a specific carpet or selecting which carpet the user is standing on.

In addition to the future work already mentioned, there is always the option to add leg tracking. Even though it was found to not be essential to the VR experience, it could still add some potential benefits.

8.2 Large scale study

So far, the work done during the thesis was focused on investigating the possibility of using virtual reality to enhance the sensorimotor walkway exercise. While it was verified that VR does indeed increase the attractiveness and does not cause any negative side effects, long term effects of using VR during the exercise are yet to be evaluated. Therefore, designing a longitudinal study to evaluate the contribution of the VR application for this exercise was a part of this thesis.

It is important to note that this study design is fairly general, as the VR application used in the study is expected to differ from the one developed in this thesis. This is mainly due to the necessary changes described in the previous section 8.1.

8.2.1 Study goals

In this study the main goal is to evaluate the impact of virtual reality on the exercise results. The idea behind using VR is that users cannot rely entirely on the visual perception and thus need to focus more on the sensation from their feet in order to describe what they feel. This might potentially increase the exercise benefits. The study should measure participants progress in order to assess whether this assumption is valid and provide data on the amount of improvement that is to be expected.

A secondary goal of the study is to evaluate the impact of the different virtual environments on the participants' progress. It was proved that it is possible to alter the complexity of the exercise through changed virtual environments and modified bridge. However, the main focus was on whether the complexity can be changed. Therefore, the next step is to evaluate the impact of complexity changes on the participants' progress.

8.2.2 Study design

For a proper study design, it is crucial to define at least two study groups. One of these groups should be a control group, others are experimental groups, which receive the variable being tested. Another key element of any study is well defined metrics. These are needed in order to compare the results of the study groups.

Study groups

Based on the defined study goals there are two tested variants - usage of a VR headset with either constant environment complexity or progressive environment complexity. Therefore, the participants of the study should be split into three separate groups:

- **Control group**: participants who exercise without the use of VR.
- **Constant environment complexity**: participants who exercise with a basic form of the VR experience, limited to the same complexity level.
- **Progressive environment complexity**: participants who exercise with the progressively changing level of complexity. The progression will be decided by the physiotherapist based on the participants' skills. This is primarily due to safety concerns, as not all the participants might be able to perform the exercise in a complex environment.

Metrics

The primary goal of the sensorimotor walkway exercise is to prevent falls by improving balance and postural stability, therefore this should be the primary focus of the metrics.

Currently, there are many studies[47] exploring the application of virtual reality for elderly individuals with focus on balance. Therefore, there are many different metrics available, ranging from dynamic balance tests to questionnaires. The following list briefly describes some of the commonly used evaluation methods:

- **Romberg test**[17]: the participant stands with feet together and eyes closed, relying on proprioception to maintain balance. The test is scored by counting the seconds the participant maintain balance.
- **Timed up and go (TUG) test**[48]: from a seated position, the participant stands, walks 3 meters, turns 180°, walks 3 meters back to the chair and sits down with back resting against backrest. Similarly, this test is scored by counting the seconds it takes the participant to complete this test.
- **Berg balance scale (BBS)**[49]: the participant performs a series of 14 tasks, such as standing up without using hands or transferring to another chair. Each task is rated from 0 to 4, where 4 is the best score.
- **Falls Efficacy Scale-International (FES-I)**[50]: is an example of questionnaire, which is commonly used in conjunction with the previous tests. It focuses on subjective measurement of concerns about falling.

After the VR application testing, it has become apparent that most of the elderly performing the sensorimotor walkway exercise lack the physical condition to perform some of the balance tests. I personally think that the

Romberg and the TUG tests are the best options as they would provide measurable data and are easy enough for the elderly to perform without any risk of injury. I would use them in conjunction with the FES-I questionnaire, as it gives insight into the subjective feeling of the patient.

It would be optimal to also use the data collected by the VR headset during the training sessions. Currently, it is possible to track the position of headset and hands and these data are available in the VR Dashboard application. Those might be used in the future for comparison purposes, however at least during the initial testing the users were often distracted by the virtual environment. This caused them to look around which, looking only at the measured data, might be mistaken as them being overly unstable. Therefore, it would be important to take this into consideration when evaluating the measured data.

Procedure

The study procedure is designed to follow the current exercise regime where the elderly exercise two times a week. Periodic progress checks should be conducted every 3 weeks, including collection of the proposed metrics.

The main issue is that the sensorimotor training conducted at the Nová Slunečnice retirement home consists of multiple exercises, some of which may include the use of VR headsets. To prevent any interference, all participants in this study should not use any VR headset for any other exercise in this routine. Moreover, the FES-I questionnaire should be filled out by each participant in private to prevent any interference from other participants.

Conclusion

This thesis was focused on the possibility of using virtual reality to enhance the sensorimotor walkway exercise, conducted at the Nová Slunečnice retirement home. During the thesis three main topics were discussed - importance of leg tracking, the design and implementation of the PhysioBridge application, consisting of the VR experience and the control application, and the design of a longitudinal study of the impact virtual reality has on the exercise.

The thesis has shown that leg tracking is not crucial for the sensorimotor walkway exercise. The absence of leg tracking did not cause the participant any negative effects in the form of VR sickness or walking difficulty. Nevertheless, the addition of leg tracking could still bring potential benefits to the VR experience in the form of more gamification options and data collection. For this, the problems with tracking precision and accuracy would need to be solved.

The designed VR application as well as the control application proved to be useable for the sensorimotor walkway exercise. Even though the testing process revealed that the VR experience increased the attractiveness and social interactions, the main purpose of the walkway exercise was hindered. This is mainly due to the fact that the elderly were more interested in the environment itself instead of the exercise. For this reason, various enhancements were proposed.

Finally, a longitudinal study to evaluate the contribution of the VR application for the sensorimotor walkway exercise was designed. The study design includes the definition of study groups as well as proposed metrics for contribution evaluation.

To summarize, the overall work in this thesis showed that virtual reality can be useful for enhancement of the sensorimotor walkway exercise. However, the design of the VR application needs to be modified in order to better support the goal of the exercise.

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Appendix A

Testing documents

This Appendix contains documents used for testing conducted during this thesis.

- User testing protocol of the leg tracking prototype
- Questionnaire used after testing of the VR part of the PhysioBridge application
- Informed consent to participate in research

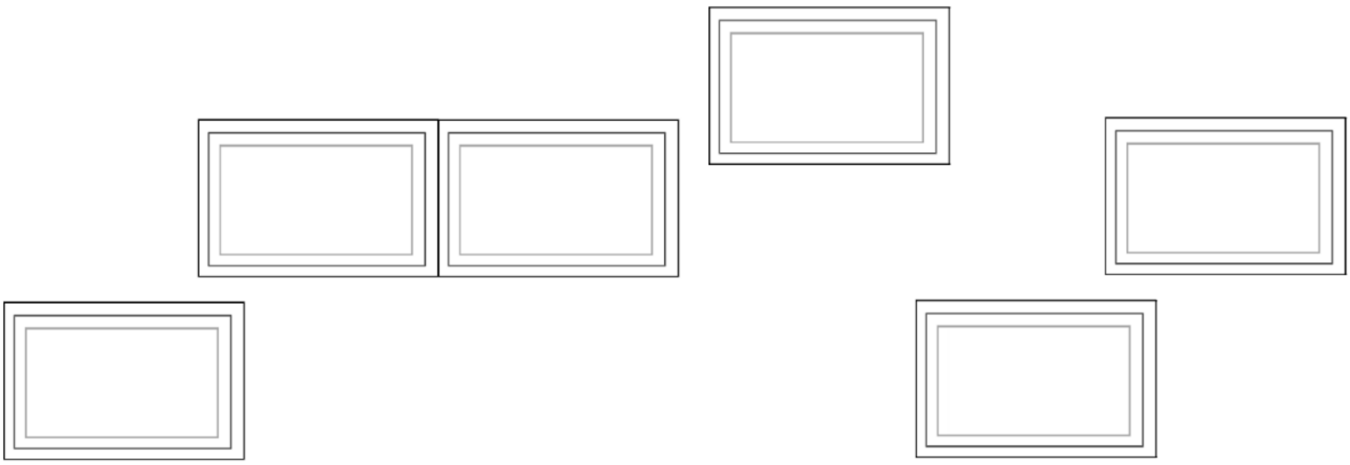
Prototype - User testing protocol

Screener

Participant id	…………………………………
Gender	…………………………………
Age	…………………………………
Length of foot (cm)	…………………………………
VR experience (yes/no - how long?)	…………………………………

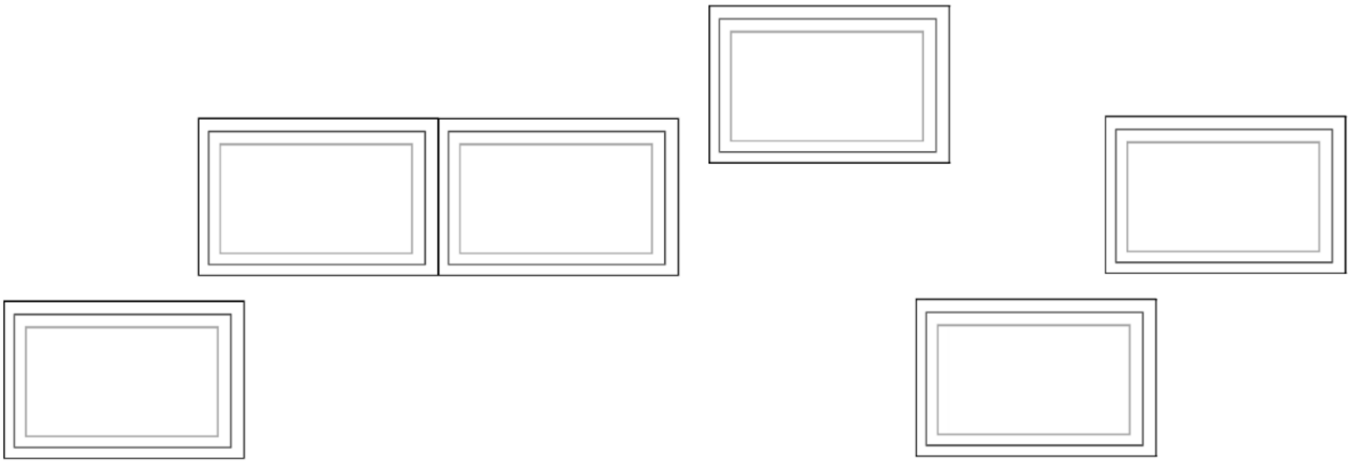
Session guide

First walkthroughs: Walking according to visualization



- **Footprints:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**
- **3D shoes:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**
- **3D Avatar:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**

Second walkthroughs: Walking only by the participants' intuition (as they think it would be the most accurate in the real world)



- **Footprints:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**
- **3D shoes:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**
- **3D Avatar:**
  - **Perceived accuracy:** (how accurate does the participant think the visualisation is?)
  - **Feeling from visualization:**

Post testing questionnaire

Did you experience any signs of VR sickness? *(nausea, tiredness, headache etc.)*

Which visualisation was the most pleasant?

Virtual Reality Research Questionnaire

Screener

Participant id *(corresponds to VR Dashboard)*	…………………………………
Age	…………………………………
Gender	…………………………………
Experience with the sensorimotor walkway	…………………………………
Experience with VR (yes/no – How long?)	…………………………………
Experience with PhysioTrails (yes/no – How long?)	…………………………………

Post testing questionnaire

VR sickness	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Nausea	1	2	3	4	5
Tiredness	1	2	3	4	5
Headache	1	2	3	4	5
Eye fatigue	1	2	3	4	5
Any other symptoms? *(Which?)*					

Attractiveness of the exercise	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Did you like the virtual environments?	1	2	3	4	5
Did you see the virtual world clearly?	1	2	3	4	5
Did you find the exercise using VR more interesting?	1	2	3	4	5
Would you like to exercise with VR on the sensorimotor walkway again?	1	2	3	4	5

Walking in VR	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Did you have difficulty any walking?	1	2	3	4	5
Were you worried that you didn't know where you were stepping?	1	2	3	4	5
Did it bother you when walking that you couldn't see your feet?	1	2	3	4	5
Did you feel like you were walking on the same materials as you saw on the first pass?	1	2	3	4	5

The complexity of the exercise	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
Did you find the walking in the second pass more difficult?	1	2	3	4	5
Were you afraid of heights on the second pass?	1	2	3	4	5
Did you find walking more difficult when you could not see part of the railing in the second passage?	1	2	3	4	5
Did you recognise what you were walking on in the second passage even though you could not see the materials?	1	2	3	4	5

INFORMED CONSENT TO PARTICIPATE IN RESEARCH

Study title:	**Validation of Usability application implementing walking on a sensorimotor walkway in virtual reality**
Lead researcher:	**Ing. David Sedláček, Ph.D.**
Institution:	**CTU in Prague**

Participant name: ....

1. STUDY PURPOSE

The goal of the project is to develop and implement an application in virtual reality that will enrich the exercises on the sensorimotor walkway carried out in the Nová Slunečnice nursing home in Prague. The main goal of the study is to verify the applicability of virtual reality for the given exercise, as well as to verify the possibility of influencing the difficulty of the exercise using virtual reality. This approach provides a unique opportunity to make the methodology more attractive to seniors while potentially increasing the effectiveness of exercise.

We hereby ask for your consent to participate in this research study. In this form you will find information about the study being conducted. We would like to make sure that you are familiar with the purpose of this study and what participation in this study will mean for you. Please do not sign this form if you do not understand any part of this text. In that case, don't hesitate to ask us anything.

Thanks to you and your opinions, we will be able to modify the product so that its use is efficient and easy.

2. PARTICIPATION IN THE STUDY

We expect 5 to 10 people to participate in this study. The criterion for selecting participants is their regular involvement in exercise on the sensorimotor walkway.

Participation in this study is voluntary. We expect you to attend one session, which will consist of a short interview followed by a user test, which is not at all demanding and does not require any preparation on the part of the user. Total session time will be approximately 20 minutes.

3. CONFIDENTIALITY OF INFORMATION OBTAINED

We will record your answers in our notes, which will be kept anonymously, and it will not be possible to identify your person retrospectively. The information will be processed during the analysis of the obtained data and will appear in the results of the project, but again only in such a way that it will not be possible to trace from whom we obtained it.

During the experiment, we can make an audio or video recording for later evaluation. The data obtained in this way will not be directly published, but will serve only for the needs of the members of the research team related to this experiment.

4. COMPENSATION OF POSSIBLE DAMAGES

By signing this document, you are not waiving your legal rights to seek compensation in the event of an injury you suffer directly related to this study.

5. VOLUNTARY PARTICIPATION AND AUTHORIZATION

Your decision to participate in this study is entirely voluntary.

6. WITHDRAWAL FROM THE STUDY OR WITHDRAWAL OF AUTHORIZATION

You can withdraw from this study at any time without any negative consequences. If you decide to withdraw from the study later (i.e. you do not want us to continue working with your data), please contact the lead researcher in writing:

- Ing. David Sedláček, Ph.D.
  Department of Computer Graphics and Interaction, CTU FEE
  Karlovo náměstí 13, 121 35 Prague 2
  Phone: +420-22435-7589

From the moment of your withdrawal, your data will no longer be processed in any further phases of the research project. However, it will not be possible to change already existing published documents or finished and submitted outputs from the project.

7. CONTACT PERSONS

For more information about your rights as a participant in the experiment, or if you are not satisfied with the way this study is being conducted, you can contact the researcher responsible for user interface testing. If you have any questions or if you suffer any harm during the study, please contact the project leader:

- Ing. David Sedláček, Ph.D.
  Department of Computer Graphics and Interaction, CTU FEE
  Karlovo náměstí 13, 121 35 Prague 2
  Phone: +420-22435-7589

8. CONFIRMATION

Check one of these options

□ I have read the information in this form
□ The information in this form war read to me by: ....

Any questions I had were answered by: ....

I voluntarily agree to participate in this research conducted by CTU FEL staff. I will receive a signed copy of this form.

Name and Surname of the participant: ....

Date: ....

Participant signature: ....

Name and surname of the
person accepting this consent: ....

Date: ....

Signature of this person: ....