KU LEUVEN

FACULTEIT INDUSTRIËLE INGENIEURSWETENSCHAPPEN

CAMPUS GROEP T LEUVEN

Virtual Reality as an Occupational Rehabilitation Tool for Stroke Patients

Developing and Evaluating a Prototype Training Environment with

Objective Progress Assessment

Tine WILDIERS

Kato WILDIERS

Promotor(en): Maria Torres Vega
Co-promotor(en): Carlos Rodriguez-Guerrero

Masterproef ingediend tot het behalen van de graad van master of Science in de industriële wetenschappen: Electronics Engineering

Academiejaar 2022 - 2023

Faculteit industriële ingenieurswetenschappen Campus GROEP T Leuven — Masterproef ingediend tot het behalen van de graad van master of Science in de industriële wetenschappen: Electronics Engineering
Academiejaar 2022 - 2023

Virtual Reality as an Occupational Rehabilitation Tool for Stroke Patients

Developing and Evaluating a Prototype Training Environment with Objective Progress Assessment

Wildiers Kato, Wildiers Tine

Master in Electronics Engineering, Faculteit industriële ingenieurswetenschappen, Campus GROEP T Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, België

Promotor(en): Maria Torres Vega
Electronics Engineering, Faculteit industriële ingenieurswetenschappen, Campus GROEP T Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, België, <maria.torresvega@kuleuven.be>

Co-promotor(en): Carlos Rodriguez-Guerrero
Mechanical Engineering, Faculteit industriële ingenieurswetenschappen, Campus GROEP T Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, België, <carlos.rodriguez@kuleuven.be>

SAMENVATTING

Wist u dat ongeveer één op de vier mensen in zijn leven een beroerte krijgt? Een beroerte kan permanente schade aan hersencellen veroorzaken, wat kan leiden tot verlamming of gevoelloosheid van het gezicht, armen en benen. In de praktijk worden patiënten die een beroerte hebben gehad toegewezen aan een fysio- of ergotherapeut om hen te helpen bij het opnieuw leren van dagelijkse activiteiten. Deze therapiesessies vergen veel inspanning en tijd van therapeuten en patiënten. De vooruitgang van de revalidatie wordt doorgaans beoordeeld door visuele observatie van de beweging van de patiënt, wat een subjectieve maatstaf is. Het potentieel van Virtual Reality (VR) als rehabilitatie tool wordt in deze thesis onderzocht, omdat wij geloven dat het de werklast van de therapeut kan verminderen, het een objectieve maatstaf voor de progressie gedurende het revalidatieproces kan bieden, en daar bovenop ook motivatie bij de patiënt kan verhogen. Deze hypothese werd onderzocht door een prototype te ontwikkelen voor een VR trainingsomgeving waarin standaard revalidatie-oefeningen werden geïmplementeerd, zoals een object verplaatsen, het herhalen van een beweging en het traceren van een voorwerp. Daarnaast werd een evaluatie van de trainingssessie beschikbaar gesteld, gebaseerd op de gegevens die door de VR-controllers werden gemeten. Om de doeltreffendheid en het gebruik van het prototype VR-omgeving te evalueren, werden drie benaderingen gevolgd. Ten eerste hebben meerdere gezonde proefpersonen de toepassing getest en beoordeeld met behulp van de NASA Task Load Index (NASA-TLX). Deze test wordt gebruikt om de waargenomen werklast van de toepassing te beoordelen. Ten tweede hebben we een sensitiviteitsanalyse uitgevoerd op de berekeningen voor de kwaliteitsscore van de beweging. Ten derde hebben we ervaren artsen op het gebied van revalidatie geraadpleegd, ons product gepresenteerd en hun feedback en mening over de toepassing verzameld. Uit de resultaten bleek dat de ervaren belasting van de toepassing voor gezonde mensen gemiddeld laag is, en dat het spel leuk is om te spelen. De controllers slagen erin om nauwkeurige en bruikbare gegevens te produceren voor de analyse van de bewegingskwaliteit. Zo kon de visualisatie tool de trainingsgegevens van de patiënten visualiseren voor de therapeuten met behulp van de spectrale booglengte (SPARC) meting voor bewegingskwaliteit. De resultaten gaven aan dat het mogelijk is om een leuke toepassing te creëren voor patiënten en artsen, die de werklast van de therapeut effectief zou verminderen en tegelijkertijd een objectieve maatstaf zou bieden voor de voortgang van de revalidatie. Uit de gebruikerstesten konden we wel concluderen dat onder andere de toepassing in de toekomst meer intuïtief moet worden en dat het gebruik van de controller-knoppen zoveel mogelijk moet worden beperkt. Ons werk toont aan dat er zeker een toekomst is voor VR als revalidatie-tool, maar dat er nog een aantal stappen moeten worden genomen vooraleer het prototype ontwikkeld in kader van dit onderzoek commercieel beschikbaar kan worden gesteld voor gebruik door dokters en patiënten.

ABSTRACT

Did you know that about one in four people experience a stroke in their lifetime? Having a stroke can cause permanent damage to brain cells, which can result in paralysis or numbness of the face, arm, or leg. In current practice, patients who have suffered a stroke are assigned to a physical or occupational therapist to help them relearn daily activities. These therapy sessions require a lot of effort, time and money from therapists and patients. Rehabilitation progress is typically assessed by visual observation of the patient's motion, which is a subjective measure. The potential of Virtual Reality (VR) for this application is researched in this thesis, because we believe it could reduce the workload of the therapist, while offering an objective measure of rehabilitation progress. This was approached by building a prototype for a VR training environment where basic rehabilitation exercises were implemented, such as point-to-point reaching, repetition of a movement, and tracing of an object. In addition, a training session evaluation was made available, based on the data measured by the VR controllers. To evaluate the efficacy and utilization of the prototype VR environment, three approaches were taken. First, multiple healthy test subjects tested the application and rated it using the NASA Task Load Index (NASA-TLX). This test was used to assess the perceived workload of the application. Secondly, we did a sensitivity analysis on the calculations for the movement quality score. Finally, we consulted experienced physicians in the rehabilitation field, presented our product, and collected their feedback and opinion on the application. The results showed that on average, the perceived workload of the application for healthy people is low, and that the game is satisfying and fun to play. The controllers were proven to succeed in producing accurate and useful data for movement quality analysis. Thus, the application was able to visualize patient training data to the therapists using the spectral arc length (SPARC) measurement for movement smoothness. The results indicated that it is possible to create an application for stroke patients and doctors, that would effectively reduce the workload of the therapist while also providing an objective measure for rehabilitation progress. From user testing we were also able to conclude that for future works, the application should become more self-explanatory and that the use of the controller buttons should be as limited as possible. Our work shows that there is definitely a future for VR as a rehabilitation tool, but there are still a few steps to be taken before the prototype developed in the scope of this research can be commercialized and used by doctors and patients.

©Copyright KU Leuven — Deze masterproef is een examendocument dat niet werd gecorrigeerd voor eventuele vastgestelde fouten. Zonder voorafgaande schriftelijke toestemming van zowel de promotor(en) als de auteur(s) is overnemen, kopiëren, gebruiken of realiseren van deze uitgave of gedeelten ervan verboden. Voor aanvragen i.v.m. het overnemen en/of gebruik en/of realisatie van gedeelten uit deze publicatie, kan u zich richten tot KU Leuven Campus GROEP T Leuven, Andreas Vesaliusstraat 13, 3000 Leuven, +32 16 30 10 30of via e-mail iiw.groept@kuleuven.be Voorafgaande schriftelijke toestemming van de promotor(en) is eveneens vereist voor het aanwenden van de in deze masterproef beschreven (originele) methoden, producten, schakelingen en programma's voor industrieel of commercieel nut en voor de inzending van deze publicatie ter deelname aan wetenschappelijke prijzen of wedstrijden.

1 INTRODUCTION

One in four people will experience a stroke in their lifetime (World Stroke Organisation (2021)). Currently, the stroke rehabilitation exercises used in occupational therapy are quite one-sided and repetitive. Traditional methods of assessing patients' improvement rely on subjective observations and self-reporting, which can be prone to bias and inconsistency. In this thesis, we aim to enhance current stroke rehabilitation practices by incorporating enabling technology in the form of Virtual Reality (VR). We propose the development of an application that utilizes VR to implement ordinary exercises in a more engaging manner. By integrating motion-tracking technology within the VR application, we can collect quantitative data on patients' movements and range of motion. This objective assessment can provide valuable insights for healthcare professionals to tailor the rehabilitation program to each patient's needs and track their progress over time accurately. In this section, we will introduce the problem statement, as well as related works around the topic of stroke rehabilitation, and discuss the objectives of this research.

1.1 Problem statement

This year, 12.2 million people worldwide will experience their first stroke and 5,7 million will survive, likely with long-term symptoms as a result (World Stroke Organisation(2021)) Furthermore, according to the Centers for Decease Control and Prevention (2023), stroke is the leading cause of serious long-term disability. The impact of a stroke can be short- and long-term, depending on which part of the brain is affected and how quickly it is treated. In the past 2 decades, stroke rates have been climbing at an alarming rate worldwide. Interestingly, although the incidence of strokes has increased by approximately 60 percent, there has been a decline in the number of strokes in Americans over the age of 75 (Hilas (2023)).

A stroke occurs when the blood supply to a part of the brain is reduced or cut off. When brain tissue does not receive the needed oxygen and nutrients, brain cells will begin to die in minutes. The most common cause of a stroke is when the brains blood vessels become narrowed or blocked; this is referred to as an ischemic stroke. Another type of stroke is a hemorrhagic stroke, this occurs when a blood vessel in the brain leaks or ruptures. For a more detailed overview of stroke and its symptoms, we refer to the UK National Health Service website[1]. Stroke survivors can experience a wide range of symptoms, including difficulty speaking, paralysis or numbness of the face, arm or leg, problems seeing in one or both eyes, headaches, and difficulty walking (Brown (2022)). More information about occupational therapy after stroke can be found at the Stroke Association website[2].

The most common complaints of patients after having a stroke are hand in-coordination and arm weakness. These are two symptoms that strongly affect the patient's ability to perform basic household tasks, such as writing, eating, picking up objects, holding and pouring liquids, etc. The target group of this thesis is limited to people who suffered a stroke and now experience mild symptoms. To be able to work through the prototype developed in this thesis, the patient needs to be able to squeeze at least slightly with their right hand.

1.2 Related works

When certain parts of the brain are affected by stroke, weakness can occur in muscles. Signals between the brain and those muscles have weakened or are completely lost. These connections cannot be restored, so they will need to be rebuilt somewhere else in the brain. This requires the same process as for toddlers who still need to learn basic things they have never done before. This progress is explained by Berthier and Keen (2006), who emphasizes that the increase in skill during the first 2 years of life is not seen by an increase in reaching speed, but by an increase in reaching smoothness. Most likely, stroke patients will be referred to acute care therapy, inpatient therapy, or outpatient therapy. It is optimal to have the guidance of a trained rehabilitation professional in this process. Neurolutions (2022) presents an overview of common activities in occupational therapy for stroke survivors. They explain what types of exercise target what kinds of occupational activity, which gave us inspiration for the implementation of certain exercises in VR.

For most stroke patients, rehabilitation mainly involves physical therapy. The aim of physical therapy is to have the stroke patient relearn simple motor activities such as walking, sitting, standing, lying down and the process of switching from one type of movement to another.

Occupational therapy is a type of therapy that also involves exercise and training. Its goal is to help the stroke patient relearn daily activities such as eating, drinking and swallowing, dressing, bathing, cooking, reading and writing, and using the toilet. Occupational therapists seek to help the patient become independent or semi-independent.

Flint Rehab (2022) describes the most used exercises for stroke patients in occupational therapy.

[1] https://www.nhs.uk/conditions/stroke/

[2] https://www.stroke.org.uk/resources/occupational-therapy-after-stroke

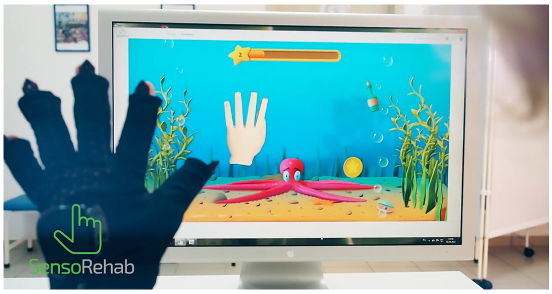

Figure 1.1: SensoRehab[3] glove.

- Level 1: Gentle hand exercises
  - Palm up and down: rotate the affected hand with the non-affected hand, for a total of 20 repetitions.
  - Wrist flexion and extension: involves stretching the affected wrist backward and then forward.
- Level 2: Moderate hand exercises
  - Rolling movement: grab a water bottle in the affected hand and try curling the fingers around it.
  - Wrist curl: This exercise is described as a bicep curl, but for your wrist.
- Level 3: Challenging hand exercises
  - Pen Spin: rotate a pen laying on a table, using thumb and fingers.
  - Coin drop: place a couple of coins on the palm of your hand, and try moving with your thumb to grip with your index finger and thumb. Then drop them.
  - Water cup pours: hold one full cup and one empty cup. Exchange the liquid from one to another, and repeat this a couple of times.

A recent study by Neurolutions (2022) has provided significant insights into motor recovery in stroke patients. The study claims that hand motor improvement can continue for up to 20 years after a stroke by participating in specific functional movements and exercises. This highlights the importance of consistently using the hand in everyday tasks. Moreover, the study emphasizes the effectiveness of repetitive activities, such as flipping cards or stacking plastic cups, in facilitating trial-and-error learning in the brain, leading to improved efficiency and ease of movement.

Furthermore, the study shows that once proficiency is achieved through repetitive practice, the learning curve levels off. While this is beneficial for learning, it is important to increase the challenge without making it impossible. The key is to find the right level of difficulty. It is suggested that once the subject successfully completes 7 out of 10 trials, it is time to raise the difficulty. For example, if they can pick up eight out of 10 wide markers without dropping them, they can be challenged by increasing speed (speed challenge), using thin pencils (motor challenge) or adding a weight cuff around the wrist (resistance challenge).

The application of intelligent rehabilitation equipment in occupational therapy is not new and is based on research by Li and Xu (2021), they point out that more hand-related assisted devices should be developed and that a digital system is also needed to collect big data. They conclude that more research should be done to find out what tools are most efficient and at what time in the rehabilitation process they should be introduced. Additionally, a systematic review on the application of Augmented Reality (AR) and VR in hand rehabilitation was carried out by Pereira et al. (2020). Their results suggest that patients can benefit from the use of Augmented Reality (AR) or VR interventions for hand rehabilitation. There are already some applications of VR and haptic feedback in rehabilitation practices. The one with the most relevance to this thesis was SensoRehab[3] (Figure 1.1). It is a haptic glove that can be used to play a 2D game on a computer screen. It is aimed at restoring hand motor function for people who have suffered stroke, cerebral palsy, traumatic brain injury (TBI), or other neurological disorders. Another VR application targeting stroke recovery is ”Diego” by Tyromotion[4] (Figure 1.2). It is used for arm-shoulder rehabilitation. The company manufactures and distributes robot- and computer-assisted therapy units for the rehabilitation sector. On a side note, there are also studies on glasses-free VR rehabilitation systems, which show that the use of VR glasses is not necessary to improve upper limb motor function in patients with stroke (Xie et al. (2021)).

To evaluate patients using these applications, a therapist must be present. With our prototype, we will try to eliminate the need for constant therapist monitoring by gathering data from the VR controller during the execution of the exercises. By processing this data we can objectively assess progress and inform therapist.

1.3 Research Objective

We believe that VR can be a solution to the bottlenecks of current rehabilitation practices and improve general rehabilitation outcomes. The research question for this thesis goes as follows:

[3] https://sensorehab.com/
[4] https://tyromotion.com/en/products/diego/

Figure 1.2: ”Diego” from Tyromotion[4]

Can data produced by current VR controller technology be used to calculate and present relevant metrics in the rehabilitation process of patients who suffer symptoms induced by a stroke, specifically reduced upper limb function?

By implementing some of the exercises mentioned above in a virtual world, patients are required to use VR controllers in their training. Due to the limitations of these controllers, we chose to implement exercises that are mainly focused on regaining arm and wrist movement. The idea is that by using these controllers, a significant amount of data is collected during training. This allows for in-depth monitoring and analysis of these movement training data. Researchers from Kauna University of Technology have already attempted to build a system to assess and recognize hand movement to track rehabilitation progress (Maskeliunas et al. (2023)). Their system uses machine learning to detect certain hand motions and succeeds with a high accuracy. With our prototype, our aim is to combine the assessment of the data with an entertaining VR experience. We believe that gathering this data will help the field of occupational therapy in three ways:

1. Motivation for the patient: There is a large discrepancy in the motivation that patients show for their recovery. Many CVA patients live inside one room due to immobility caused by stroke. VR offers them an escape, since the technology is at a point where it is possible to create very realistic scenes that make the player feel like they are actually in another world. In VR it is possible to create the same basic hand movement exercises, in multiple different layouts. The patient performs the same exercise, but they feel like they are doing something else every time because the environment might change. Basic analysis of training data can also be presented to the patient after each training. Seeing the progress they are making will motivate them to train more.

2. Analysis of movement data: Analyzing and processing the VR controller data will allow for an objective measure of quality of movement. Progress in the movement score can be linked to exercises performed by the patient.

3. Reducing the workload of occupational therapists: In current clinical practice, the patient's rehabilitation progress is typically assessed by visual observation of the patient's movements and questionnaires. This current measurement and assessment technique requires additional effort and follow-up by the physiotherapist. An automated system that the patient can even use at home without the presence of a professional could provide the therapist with numerical metrics to assess the rehabilitation progress of a patient.

Although occupational therapy can be effective in improving hand and arm function after stroke, it often relies on repetitive, one-sided exercises that can become boring for patients. This can lead to decreased motivation and decreased commitment to therapy, which can ultimately negatively influence progress. Additionally, access to traditional therapy can be limited due to factors such as cost, location, and availability of therapists.

Addressing the challenge of rehabilitation, especially in the hands, is the main subject of this thesis. The goal is to improve overall rehabilitation outcomes and ultimately help patients regain their independence and quality of life.

2 ARCHITECTURE

The architecture of our application, as depicted in Figure 2.1, begins with the utilization of the Meta Quest[1] VR device. Through this device, users can immerse themselves in a Unity-created[2] virtual environment. The VR environment actively captures and transmits controller data to a locally hosted database residing on a server within the network. Subsequently, the visualization tool accesses this database through the same network, to show a dashboard of useful information to the doctor/patient.

The goal of our application is first to motivate patients to practice the exercises administered by their therapist and continue practicing them for a long time. Second, we aim to collect information about the progress of the patients and the execution of the exercises. Third, our visualization platform should be able to show the therapist useful information about a training done by a patient, and offer a page for the patient, where they can see their own progress.

The components of this architecture will be discussed in more detail in this section.

[1] https://www.meta.com/be/en/quest/products/quest-2/
[2] https://unity.com/

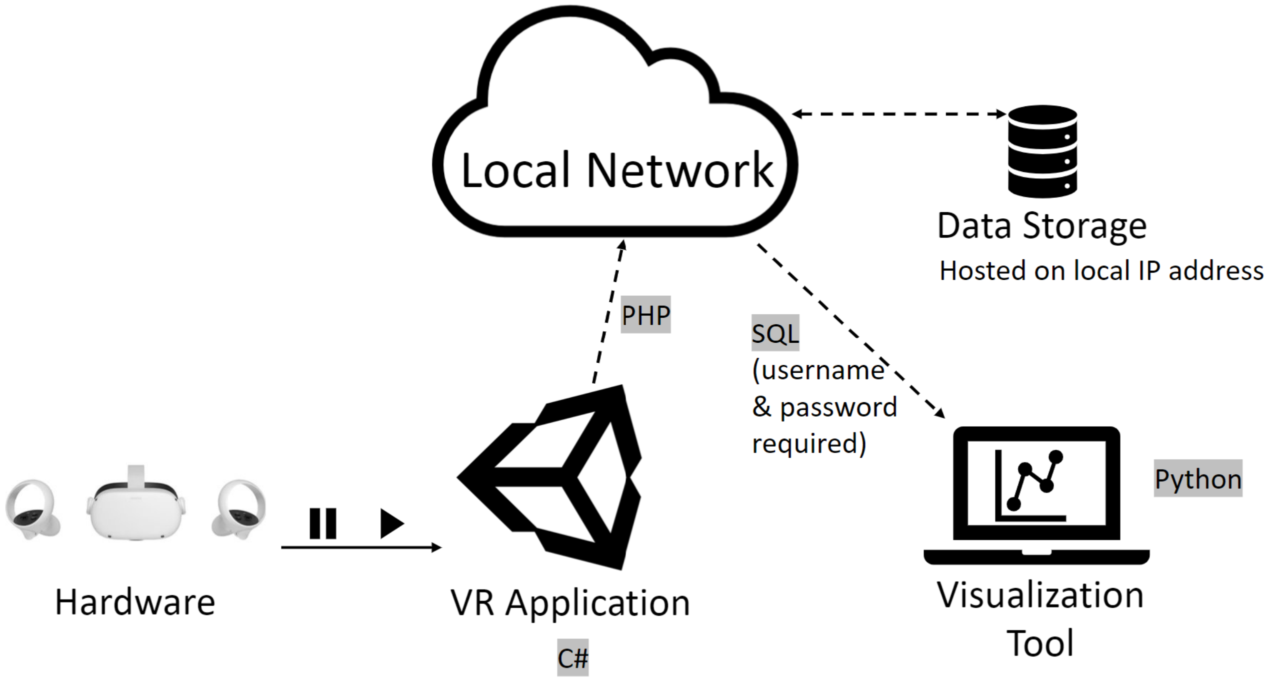

Figure 2.1: Overall structure of the prototype designed for this thesis.

Figure 2.2: Meta Quest 2 headset[3]

Figure 2.3: Meta Quest 2 controllers[4]

2.1 Hardware selection

There are several VR headsets that are widely available on the market. The available headsets were compared on the basis of price, availability, documentation, and developer support. For this thesis, the Meta Quest 2[3] was chosen (Figure 2.2), because of its well-documented API, accessibility, and integration with Unity. Various sources also point to the Meta Quest 2 as the most popular VR headset out there (CNN Underscored (2023)), and state that it has a bright future in medical applications (Klimek (2020)).

The controller used in the VR environment also functions as the sensor used for data analysis. The Meta Quest 2 includes 2 controllers[4] (Figure 2.3). These controllers consist of the following input methods: capacitive face buttons, capacitive joystick, capacitive touch pad, capacitive index finger trigger, middle finger trigger, and partial finger and thumb tracking via capacitive sensors.

The Quest 2 controllers have a maximum tracking frequency of 60 Hz. The controller uses 6 depth of field outside-in tracking by the headset's cameras. All of these inputs result in the following signals that can be analyzed:

- Location on X, Y and Z axis
- Orientation on X, Y and Z axis
- Trigger levels of index and middle finger

[3] https://www.meta.com/be/en/quest/

[4] https://www.meta.com/be/en/quest/accessories/quest-2-controllers/

Taking into consideration all these features, we decided to build our prototype based on the Meta Quest controllers. They offer great compatibility with Unity and the Meta Quest headset, and allow us to accurately measure and analyze hand movement, making them performant enough to obtain our research goals.

It could also have been interesting to use controllers with haptic features. The added benefit of haptic feedback in VR games was investigated by researchers from the Scuola Superiore Sant'Anna, Pisa, Italy (Camardella et al. (2023)). They applied haptic technology to a VR game for neuro-rehabilitation of children. Their results showed that haptic feedback can lead to higher movement smoothness. Quite a few measuring devices have already been developed, such as the measuring device by Zhou and Hu (2005), the Noitom Hi5 gloves or the SenseGlove Nova. An interested reader is referred to Appendix C for a more detailed overview of these haptic devices.

2.2 VR Application

In this section, we will discuss how we designed the VR environment to achieve the three main application goals mentioned above. We used Unity as game development platform, and imported the XR Interaction Toolkit from the Unity Asset Store, which offers a high-level, component-based, interaction system for creating VR and AR experiences. We also use the Oculus Integration package to facilitate development for the Quest 2.

The game consists of multiple scenes through which the player goes in a certain order. They will start by logging in or creating an account. Before playing any games, the player will first automatically enter a calibration scene to assess their range capacities. After this scene, they can choose which game they want to start playing; either the kitchen or the painting exercise. After playing the games, the player can leave the VR environment (or do the exercises again). In this subsection, we walk through the gameplay in more detail.

2.2.1 Login scene

In the first scene of the game, when a patient starts the exercise, he is asked to create an account or log in. This way, their exercise data will later be inserted into the database under their own userID. When they are logged in, they will proceed to the calibration scene.

2.2.2 Calibration scene

Whenever the patient starts a new training session, they will be asked once to calibrate their range. To obtain their maximum range capacity in each dimension, they are asked to move a ball as far as possible along 3 axes. Figure 2.4 and Figure 2.5 show the scene before and after calibration. The range values are stored as a global variable and later accessed by the exercise scenes to set the distance to different objects according to the patient's capacities.

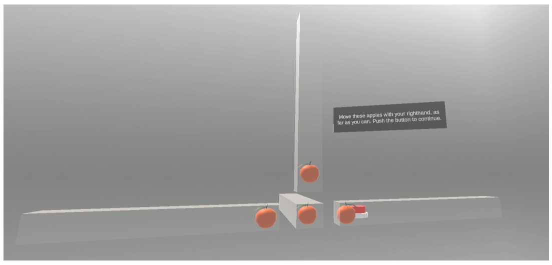

Figure 2.4: Gameplay screenshot from calibration scene before calibrating.

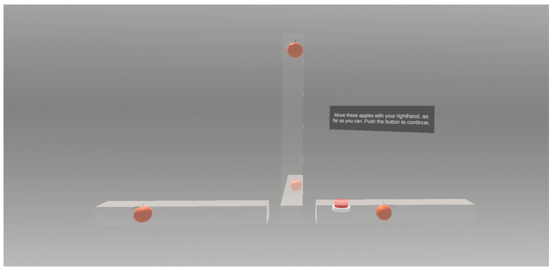

Figure 2.5: Gameplay screenshot from calibration scene after calibrating.

2.2.3 Menu scene

From there on, they enter the main section in which they can choose to start an exercise. After every exercise, they return to this page and can choose to play another game.

2.2.4 Kitchen scene

In the kitchen scene, the patient will serve as a barista. They will be asked to prepare different orders for customers. Each order is put together at a different spot in the kitchen. At each spot, the objects to be served are placed further and further away from the patient, within their pre-defined range from the calibration scene. This scene contains 3 levels, where the difficulty is increased each level.

In level 1, they will be asked to reach for objects at a distance of 30 percent of their maximum reach. Level 1 consists of putting a coffee and a cupcake on a plate. The player has to fill the coffee themselves, by putting the cup under the coffee machine and activating the machine by pressing the button.

In level 2 the distance between the objects that need to be grabbed is greater (50 percent of their maximum reaching distance), making it more challenging.

The same goes for level 3, where the objective is to collect a couple of apples in a basket. The apples are scattered throughout the table, all at maximum reach distance.

An important aspect to ensure motivation in VR environments is performance feedback (Caldas et al. (2022)). In the first two levels, clear sockets are provided so that it is obvious to the user where the objects of that level should be placed. The sockets keep track of their content so that when all elements are put correctly, the user will hear and see feedback that the order is completed. This scene mainly includes point-to-point reaching movements in different directions and grab and release movements.

Figure 2.6: Gameplay screenshot from the kitchen scene.

2.2.5 Painting scene

The painting scene allows the player to get creative. They stand before a painting canvas, and a couple of colored grabable objects, which represent paintbrushes. Moving the paintbrushes over the canvas results in permanent marks, making it feel as if they are really virtually painting. The first drawing to complete is one of a rainbow. This way, we obtain 5 repetitions of a straight-line movement. Next, they are asked to trace a ring on the drawing canvas to obtain three different shapes; a square, a house, and a circle. We use the calibrated range values to set the boundary of the ring so that the patient can always reach it. We also increase the speed of the ring to see if it affects the smoothness of motion. The player will continuously see feedback when they are painting correctly (paint appearing on the canvas), and also hear a paintbrush sound.

Figure 2.7: Gameplay screenshot from the painting scene.

2.3 Data Storage

To store all the data generated by the controllers, a relational database is hosted on the laptop that runs the VR environment. Because of the scale of this thesis, the PC was set up to be a server on the local network, so the database is only accessible when this PC is turned on. The database can be accessed by other users of the same network, if they have the right login information. The layout of the database is as follows: there is one table to store all user data. Username, first name, last name and a user ID are stored here. There is another table to store all the training information, such as when a game was played, by who, and which levels they completed. There is one more table, where all the raw training movement data is stored. In this table, the X,Y,Z positions of the hands are stored, together with the speed and acceleration in game. This layout was implemented to make visualization and analysis easier.

Through scripts in Unity, we control what kind of data is pushed in each level, together with the right level ID's to make sure the data in this table is distinguishable from other levels. The information is pushed to the database through PHP scripts. Inside these scripts, SQL statements are constructed with the needed information. This happens in real-time and wirelessly. When a player completes an exercise, the results appear immediately on the visualization platform.

2.4 Visualization platform

A visualization platform was set up, meant for patients and doctors, to track the rehabilitation progress in a similar manner as the feature based approach proposed by Roshanak Houmanfar and Kulic (2016). An example of all the tabs in the visualization platform can be found in Appendix A.

Before accessing the user data, the username that was given in the VR environment prior to playing the game, is needed. If a valid username is given, the visualization platform will automatically select the most recent training to visualize. A dropdown menu will appear where the user can select previous trainings for visualization if desired.

The first tab contains the overall training data. Based on the feedback of experts, we left out raw numbers from this tab, and only display progress figures. This makes it easy to see the progress in patient training at a glance. The kitchen tab separates the first exercise in 3 levels, each of these levels are analysed and visualized. The smoothness measure works best on very discrete signals. That is why first a smoothness score is given to the distinct movements of moving one object, and afterwards we take an average of all these smoothness scores. For this exercise also the average speed is shown, and if the patient completed all of the objectives.

The painting tab analyses the second exercise. Users can see how well they managed to draw the painting, and an analysis is done on these signals as well. The smoothness for the discrete movements is calculated, and also a measure of accuracy is calculated, indicating how good the patient was able to track the circle.

On the visualization platform, movement smoothness is used to assess the quality of movement. According to a study by Balasubramanian (2015), smoothness is one of the most relevant measures for movement quality. In their study, multiple smoothness calculations were compared to one another, and they concluded that their proposed measure outperformed existing measures in detecting differences in smoothness between movements. The method they propose is called the Spectral arc length method, or SPARC. Another method that comes close to this is the LDLJ method, which stands for log dimensionless jerk. Balasubramanian proves in his publication that only SPARC and LDLJ are valid smoothness measuring methods. In the paper, also other measures like dimensionless squared jerk were mentioned. Another researcher Hogan and Sternad (2009), also describes this method as the most accurate one at that time. However, Balasubramanian's research indicates with a sensitivity analysis that SPARC is still a better method, because it is more time-independent. For smoothness calculation, we will thus use the SPARC method. This method requires a speed signal with periodic sampling. The data from the VR controllers themselves is not sampled periodically, but sample times range from 15 to 30 ms. We used a python interpolater on the signal to force a sampling rate of 12 ms, thus creating a signal virtually identical to the original one, but with a constant sampling rate. The controllers provide a position measurement accurate to the micrometer. This value is used to calculate speed, which is used to calculate smoothness.

The entire analysis written by Balasubramanian can be found online on github[5]. The code for the visualization platform is also available on github[6].

3 EXPERIMENTS

Will people who are in need of it, actually use this application, instead of the traditional occupational therapy exercises that are available?

That is the question that we are trying to formulate an answer to with the experiments discussed in this section. Since the application is both for physicians and patients, this question must be posed for both of these target groups.

We took three approaches to evaluate and validate our prototype. First, to assess if our prototype could actually motivate people, we asked several healthy test subjects to play through the training and gathered their opinion. We included people of various generations, ranging from age 20 to 78. Secondly, we performed a sensitivity analysis using the SPARC method on the data. Thirdly, we consulted experienced physicians in the rehabilitation field; one physical medicine specialist, and one former occupational therapist.

3.1 Healthy test group

To evaluate the effectiveness and user experience of the application, we will use the NASA Task Load Index (TLX)[1]. The NASA TLX is a widely recognized and validated subjective assessment tool used to measure workload and task performance in various domains, including healthcare and technology (Agency for Healthcare Research and Quality (2010), Li et al. (2023)). The first part of the test is a questionnaire that divides the total workload into six subjective subscales; Mental Demand, Physical Demand, Temporal Demand, Performance, Effort and Frustration. The second part creates individual weightings of the subscales based on their perceived importance. These weighted ratings are combined to the task load index. By incorporating the NASA TLX into our experiments, we can gather valuable insights into the cognitive demands, perceived effort, and overall task load experienced by healthy patients while using the VR application. This evaluation will provide us with quantitative data to assess the usability and effectiveness of the application, allowing us to identify areas for improvement and tailor the rehabilitation program to meet the specific needs of each

[5] https://github.com/siva82kb/SPARC

[6] https://github.com/Thesis-VR-Haptics/VR-Data-Dashboard.

[1] https://software.nasa.gov/software/ARC-15150-1A

patient.

Additional questions were also asked in an interview with each test subject to get more insight into the motivation of the patient to continue training with this tool. An overview of these questions can be found in appendix D.

The protocol for testing followed these steps:

1. Short presentation for the test subject, explaining shortly the objectives of the game and the different levels.
2. Game setup so that the test subject enters the calibration scene at once.
3. Test subject plays through the game five times.
4. Visualization tool is shown to the subject with their data.
5. Interview with focus on motivation to continue training with this tool.
6. NASA TLX questionnaire.

3.2 Sensitivity Analysis

In order to evaluate the accuracy of the smoothness score, we conducted additional tests involving the replication of a sine wave that mimicked one of our own healthy movements. By comparing the smoothness results, we aimed to validate the effectiveness of our scoring method

3.3 Rehabilitation experts

The protocol for testing with the (occupational) therapists followed these steps:

1. Short presentation for the test subject, explaining shortly the objectives of the game and the different levels.
2. Game setup so that the test subject enters the calibration scene at once.
3. Test subject plays through the game once.
4. Visualization tool is shown to the subject and discussed in detail.
5. Interview with focus on questions about the visualization tool, and the potential of VR in the field of occupational therapy. An overview of these questions can be found in appendix D.

4 RESULTS

To evaluate the prototype, we will now look at the results from testing with the healthy test group, evaluate the quality of the data analysis, and finalize with the therapist interviews.

4.1 User study results

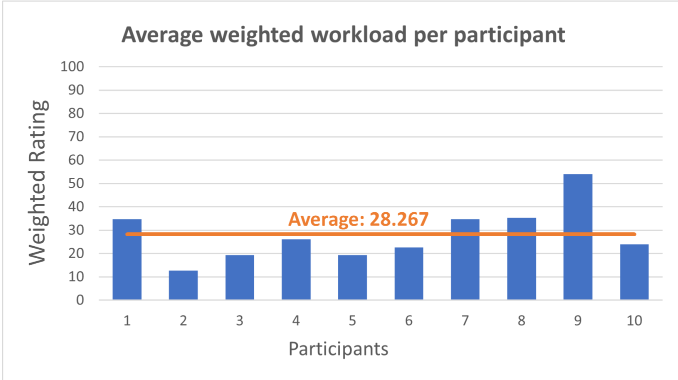

Figure 4.1: Average weighted workload per participant.

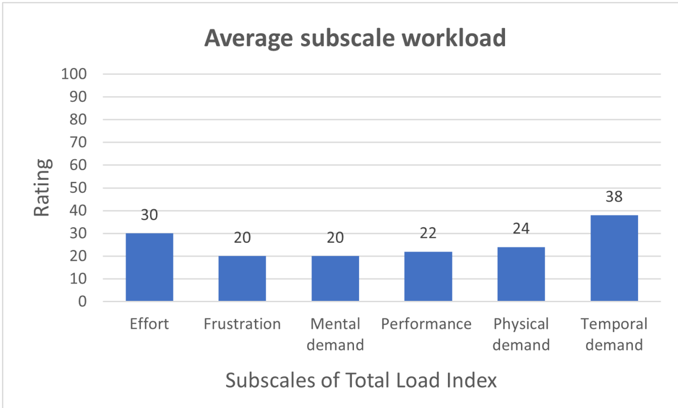

Figure 4.2: Average rating per subscale.

In Figure 4.1 and Figure 4.2, the results of the NASA-TLX questionnaire are displayed. On the first figure, we can see that the Total Load Index is 28.267. On the second figure, it is noticeable that the Frustration, Mental Demand, Performance and Physical Demand subscales score relatively low, and the Effort and Temporal Demand score a little higher with 30 and 38 respectively.

In terms of gameplay, the answers to our open questions were positive. Of all age groups, all people found the exercises fun to play. They indicated that the environment was nicely designed, and that the exercises, although quite easy, were intuitive to play and fun. We noticed that young adults tend to understand and master VR technology faster; we did not need to explain how to hold and use the controllers to them, in contrast to the older-aged subjects. The older-aged subjects also appeared to have more issues with the VR headset.

We also showed the visualization platform to the test subjects, to show the capacities of the controllers and how progress is visualized. All test subjects indicated that presenting progress data would stimulate and motivate them to exercise more often, and that the application would probably cause them to exercise more than the usual home exercises administered by therapists.

Figure 4.3 depicts a summary of the test results. The movement quality progress plot from the 10 test subjects were combined, and an average movement quality progress plot was constructed (Figure 4.4), which indicates that even for healthy subjects, there is an improvement in movement quality when repeating the exercise a couple of times.

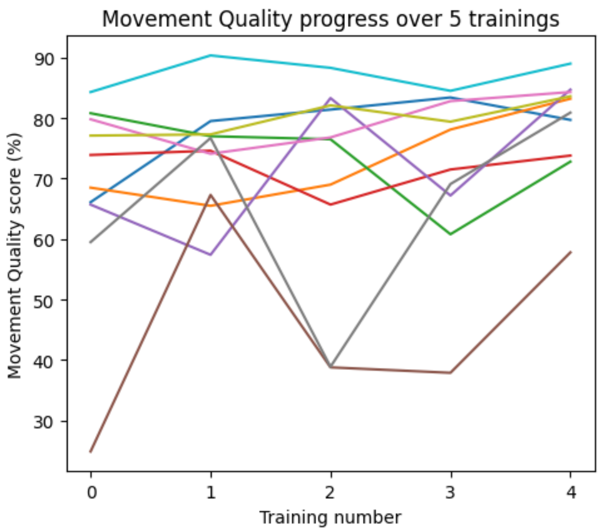

Figure 4.3: Overview of movement quality scores for each test subject's 5 trainings. Each line represents a different user.

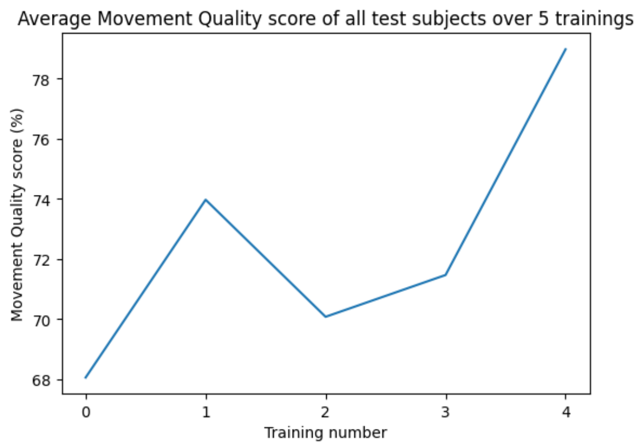

Figure 4.4: Averages of Figure 4.3, indicating the average progress in movement quality over 5 trainings from a healthy test subject.

4.2 Data analysis results

In the visualization tool, the two markers that are used to calculate the quality of movement, are smoothness and range. Range is an easy-to-measure value, which is measured in the calibration scene.

According to Balasubramanian (2015), a point-to-point movement of a healthy person should result in a smoothness score of -1.6. The closer to zero, the smoother the movement. This was tested by first of all, doing a lot of measurements ourselves with different degrees of smoothness. This consistently led to scores that became worse for less smooth movements. We noticed that for point-to-point tasks, it was easy to compare the different exercises. However, in the painting exercise there is also an exercise where the patient is asked to draw a circle. The smoothness score of this movement, was consistently much worse than the point-to-point movements, indicating that the smoothness score is task dependent, as mentioned in Balasubramanians research.

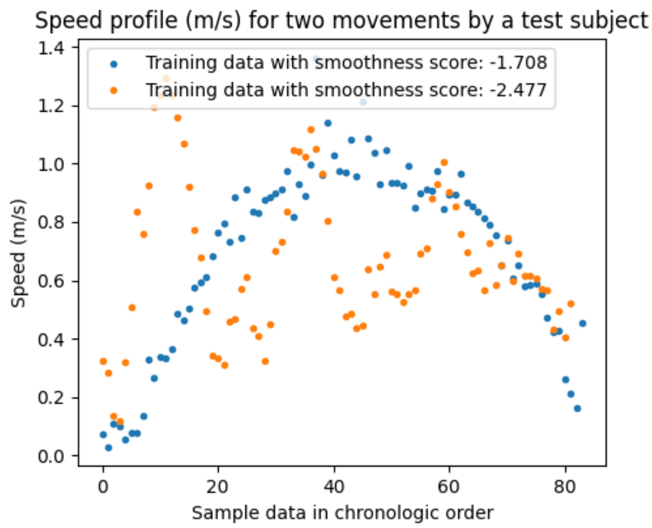

Figure 4.5: Graph with the speed signals (m/s) of one normal movement and one movement where the test subject added a tremor to their hand.

Figure 4.5 illustrates two movements performed by a test subject. The first movement was executed as smoothly as possible, while the second movement involved deliberately introducing hand vibrations during the motion. As anticipated, the smoothness score for the second movement (-2.477) was noticeably worse compared to the first movement (-1.708).

Figure 4.6 demonstrates a constructed sine wave based on the initial movement depicted in Figure 4.5. Both blue signals in the figures are very much alike, one being a real movement and the other one being a sine wave depicting this movement. The smoothness score for the real signal was -1.708, while the smoothness score for the sine wave

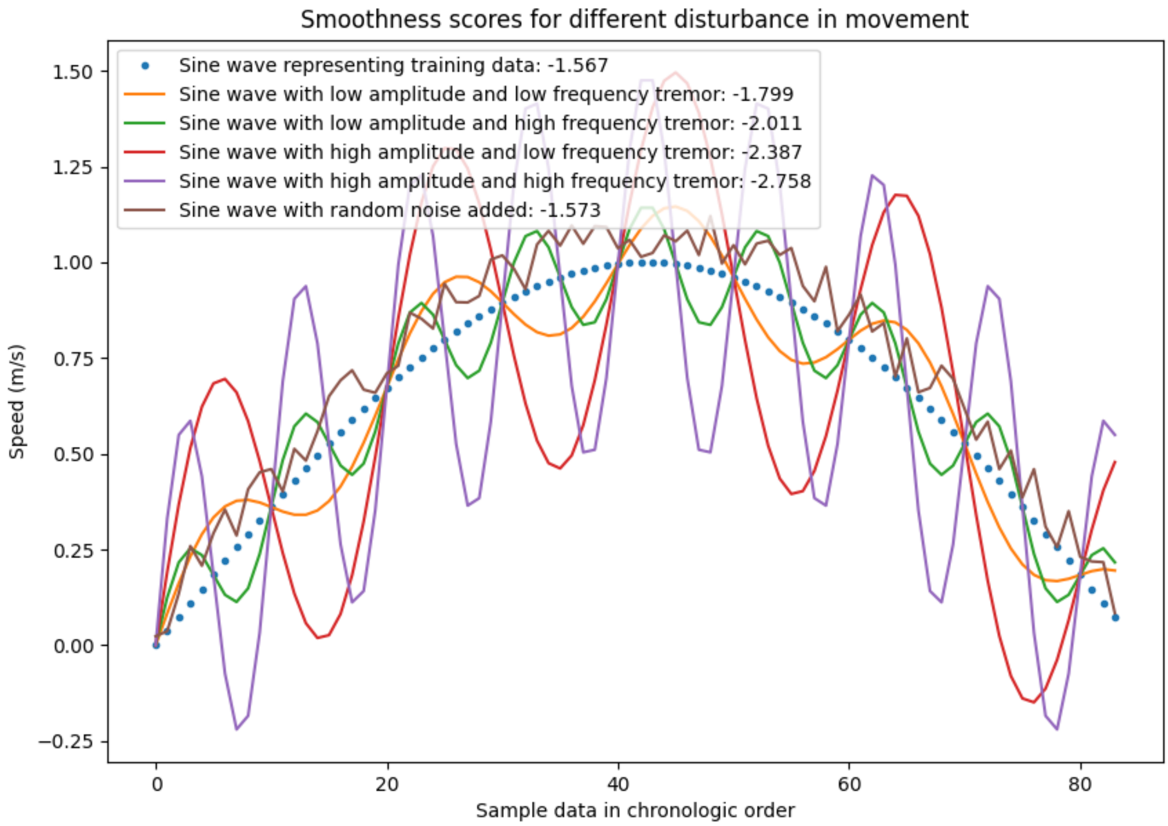

Figure 4.6: Sensitivity analysis on the SPARC method.

based on that signal was -1.567. To assess the impact of disturbances on the smoothness score, we generated additional sine waves derived from this original waveform, with variations introduced. It was expected that signals representing a sine wave or a bell-shaped curve would yield the highest possible smoothness score. We explored the effects of augmenting the original signal with high and low frequencies, as well as varying amplitudes. The results of this analysis can be found in Figure 4.6.

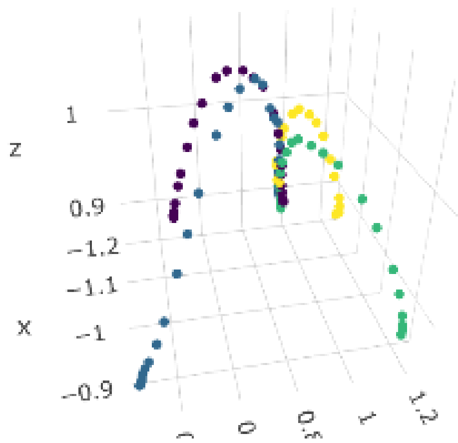

Figure 4.7: Screenshot from visualization tool, showing a 3D plot of the apple exercise.

4.3 Interviews with (occupational) therapists

In general, the therapists remarked that the combination of a 3D plot of the movement (Figure 4.7), together with the speed profile (Figure 4.8) and the movement quality score has a lot of potential in the field of occupational therapy. Physicians can clearly see how the hand of the patient moved, and notice if there are problems in general or with moving in specific directions. One point of feedback on these plots specifically, was that it could be even more helpful to also add the orientation of the hand to these plots. This would tell them more about the orientation of the wrist as well, which helps with estimating how correctly the movement was executed.

The same was said about the training tab. Specifically the progress of the maximum range over time (Figure 4.9) in each direction was identified as useful marker for rehabilitation progress. The combination of all these plots results in a tool that therapists can use to determine if they need to make changes in the training schedule of a patient, by making them easier or harder. This decision can

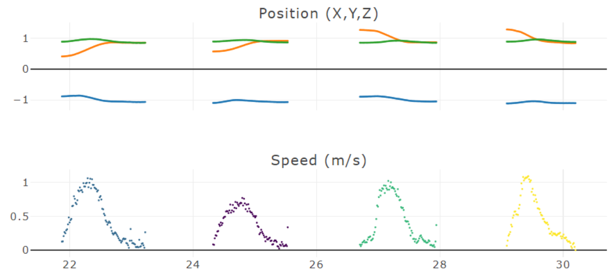

Figure 4.8: Screenshot from visualization tool, showing the speed plot for the movements from image 4.7

be made with a quick look at the visualization tool, instead of a patient visit that requires monitoring throughout the entire training, thus effectively reducing the workload for a physician.

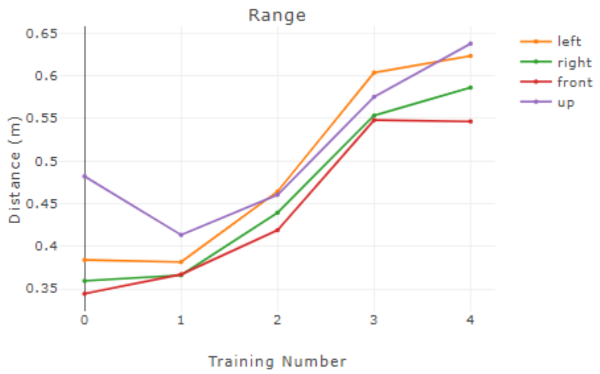

Figure 4.9: Screenshot from visualization tool, showing the maximum ranges in each direction for the 5 trainings this test person did.

From our conversation with physical medicine specialist P. Wildiers, we got the following insights:

- Virtual reality could offer added value to rehabilitation exercises due to its immersiveness. He explained that in CVA, it is not the muscle itself that limits the movement of the patients. It is the brain that has lost the ability to control the muscle. He made an association with another exercise called hand mirroring; when your left hand is affected by the stroke, they place a mirror next to your right hand and make you move that hand around. In this way, it looks like you are moving your left hand. The purpose of this is to trick your brain into thinking that your left hand is moving, stimulating it to repair the brain connections associated with moving your left hand. He estimated that with VR, the effectiveness of rehabilitation exercises could be even greater, because your brain is more immersed, more captivated by the game.

- An issue in current rehabilitation practices that he mentioned, is that you cannot control or check how well patients are doing their homebased exercises. Having an objective measure could give him proof that the patient is doing his exercises and offers an overview of their progress over a long period. This is not only beneficial for the quality of treatment, but also for motivation. Presenting qualitative proof of progress, could be an additional motivation for the patient.

- Not all patients will intuitively understand how to play the game. He compared this to an exercise that is already being used in physical therapy. It is a Wii game, where a patient needs to stand on a platform and can move a ball by shifting their weight on the platform. The only thing that happens is a bal on a TV screen and the platform. It is very intuitive to play, and patients can start immediately. He said we should try to make our game more intuitive in a way that you just give some instructions in advance, but the gameplay should be simple.

- He also mentioned that it is normal for a therapist to have to explain certain exercises to patients. To tackle this, we adapted our game by removing some abundant text explanations and creating an instruction powerpoint that contains some pictures of the game. For all the test persons, we first went through this presentation and gave a short explanation.

From our conversation with occupational therapist W. Habils, we got the following insights:

- While there already exist some digital applications for patients, they are mostly hospital applications bound and cannot be used without a therapist near. An example of this is the Gentle/s prototype developed by Rui Loureiro and Harwin (2004). The step towards creating a product that helps and motivates patients to do their exercises at home correctly is a very big and important one.

- The VR glasses are quite heavy, making them unusable for patients with very severe symptoms. Due to this, it is important to clearly define how far the patient needs to be in the rehabilitation process to be able to work with this tool.

- The rainbow exercise specifically was not clear at first sight.

- A big point of feedback was also that the patient is still allowed to move completely wrong and have a score of 100 percent. The prototype does not hold the rotation of the hand in account. In patients with stroke, it are often the upper arm muscles that remain the strongest, causing patients to do grab movements by using their upper arm to move their hand to a certain position, without using forearm muscles to orient the hand in a certain way.

- At the moment there are not enough resources to provide each patient with daily help, but that would be very useful to their rehabilitation process.
- Selecting buttons on the controller is beyond the capabilities of most patients.
- Some more feedback on future ideas for the project. These will be mentioned in the future work section of the next section.

5 DISCUSSION

We will analyze the results by first discussing the objective results, followed by a discussion of the research objective, and finish with a Future Works section.

5.1 Discussion of the results

We believe that the results of the NASA-TLX questionnaire and the interviews with the test subjects, indicate that the VR application that was created would actually be used by patients who are in the process of stroke rehabilitation. The results of the NASA-TLX questionnaire for healthy test persons gave us an idea of the experienced workload of the application. With an average Task Load Index of 28.267, we conclude that the exercises are accessible and easy to play for healthy persons. Temporal Demand had an average score of 38. It represents how much time pressure the players feel due to the rate or pace at which the tasks occur. This medium score probably comes from the painting exercise where the players need to follow the ring at a certain pace. The feature of Performance, which stands for how satisfied a person is with their performance and how successful they were in completing the task, had an average score of 22. This is positive, since the scale for that feature went from '0 = perfect' to '100 = failure'. This low value therefore indicates that playing the game results in a certain level of satisfaction.

In addition, there were some insights about the game that we gained by going through the test subject's data. In general, test subjects scored better on the kitchen exercise than on the painting exercises where they had to follow an object with a marker. This is likely due to the fact that in these exercises, the test subject is forced to follow an object and thus cannot choose how fast they will move. The rainbow exercise was also discussed with the therapists, as it was meant to be an exercise similar to repetitive exercises in occupational therapy. In the data from test subjects (an example can be found on figure 5.1), there wasn't a clear pattern where the movements became more smooth after a few tries. The plot shows the 3D movement, and the movement quality score per rainbow stroke. The lack of a clear pattern is likely due to the fact that the different parts of the rainbow were too far apart from each other, so the movements were not enough alike to facilitate improvement. It was also often the case that the highest part of the rainbow was the biggest challenge for test subjects, because it required them to raise their arm as much as possible.

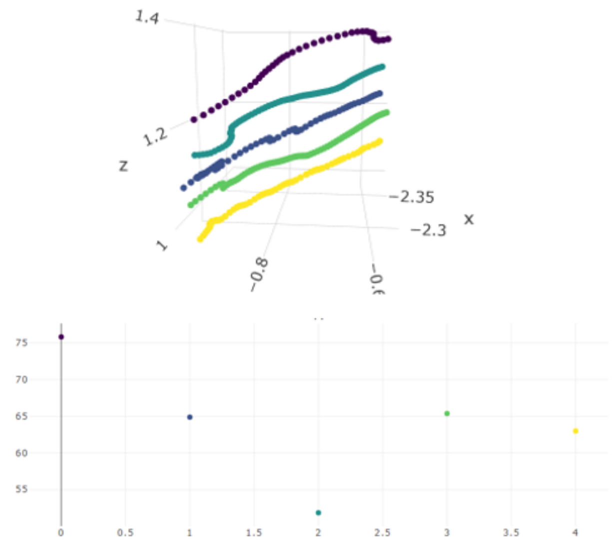

Figure 5.1: Screenshot from visualization tool, showing a 3D plot and movement quality scores for the rainbow exercise.

The experiments on data analysis and the use of the SPARC method reaffirm the validity of the smoothness score by employing a variety of test scenarios. The findings indicate that deliberate vibrations with high frequencies and large amplitudes introduced to the original movement adversely affect the smoothness score. Unexpectedly, the addition of random noise has a relatively minor impact on the overall smoothness score.

We found various sources that support the remarks made by the therapists. The hand mirroring exercise for example is a wellknown exercise, and has been proven to work (Perez-Cruzado et al. (2017)). The importance of visual feedback for motor learning is also described by Doeringer and Hogan (1998). More of their feedback will be discussed in the future works section.

5.2 Discussion of research objective

The objective of our research was discribed in the Introduction. Our initial research question is the following:

Can data produced by current VR controller technology be used to calculate and present relevant metrics in the rehabilitation process of patients who suffer symptoms induced by a stroke, specifically reduced upper limb function?

Based on the results, we will now discuss to what extent our research question can be answered. We will tackle this by looking at how qualitative the calculated controller data is and how successful they are in presenting relevant data. The calculated data has been shown to be an accurate representation of hand movements during rehabilitation exercises. The VR controllers used to develop the prototype provide sufficient and adequate data on the movement of the player. The most important measures acquired from the raw data are smoothness and range. With these values, it is possible to calculate and analyze the quality of movement objectively. The visualization platform developed to display the processed data has the ability to present caregivers a quick overview of the progress of the patients. It can give them insight into how regularly their patients are executing their homebased exercises, how well they are executing them, and how their smoothness and range are progressing over time.

In addition to the research question, 3 goals were described in the Introduction to help improve the field of occupational therapy for stroke patients. These goals were to first have a fun game to play and keep the patients motivated. Second, we wanted to collect and display data in a functional and intuitive way so that caregivers can easily interpret the patient's progress, and third, we wanted to reduce the workload of occupational therapists. Based on the previously discussed results, we can conclude that

1. All test subjects found the exercises fun to play. The exercises are adapted to the abilities of each individual player. By storing their results and showing their progress, we can motivate them to continue practicing. We cannot draw a hard conclusion on the permanent motivational aspect of the application, since none of the test subjects actually did the exercises over a longer period of time.

2. With the Meta Quest 2 controllers, we are able to obtain a measure for smoothness and range. These values are used to determine the quality of movement of the players and displayed per exercise on a webserver. Therapists can access this webserver and gain insight into how well their patients are performing on the VR exercises.

3. By offering remote information on the progress of patients, we can reduce the workload of occupational therapists. By giving them an objective measure of the execution of the exercises, there is less need for a time-consuming visual observation of each patient.

5.3 Future Works

During the research a lot of tips were gathered from patients and expert physicians. In the following section, this feedback will be discussed in order of importance.

1. Clearly define the skill level needed from a patient to be able to do this specific exercise.

2. Make it clearer and more intuitive what is expected from the patient. Hold into account that the patients are mostly from an older generation, and not quite used to this type of technology.

3. Remove the button implementation and make sure patients can select objects by squeezing the controller in general.

4. Include feedback about how correct the movement of a patient is, arm wise. This comes down to also taking into account the rotation of the hand while doing the exercise. For point to point reaching specifically, this could for example be done by implementing a machine learning algorithm that is trained to recognize a healthy movement. Solutions like this have been hinted to previously, by for example the template matching based motion classification for unsupervised post-stroke rehabilitation developed by Zhe Zhang and Barrett (2011).

5. Include the correctness of movement in the visualization platform.

6. Implement more feedback, both visual, auditive and haptic.

7. Make it so that there is a version for training at home and training at the hospital. The hospital training can be more challenging than the home training, because the doctor can supervise it there.

8. Add control for the doctor, so that they can change the difficulty of exercises remotely, depending on how well the patient is doing them. It might be more useful to perform an easy exercise with the right motion, than to perform a hard exercise incorrectly.

9. Add more levels, both more and less extensive in environment. Some people will enjoy special surroundings like space, a fancy room, outside. Others will prefer a very basic surrounding so they can focus purely on the training itself.

10. Extend the target group for the application by also making available easier and harder versions, implementing more of the traditional exercises.

11. When a VR glove technology becomes widely available at an affordable price, implement it as well in the training. Individual finger tracking could also be used to further analyse tremors in the fingers and what they origin from, based upon research from for example Carlijn Andrea Vernooij and Reynolds (2014)

From this evaluation, we conclude that a VR game could definitely improve the rehabilitation field. It could enhance repetitive exercises with entertaining games, while assessing objective progress information. This is not only beneficial for the quality of treatment, it can serve as an additional motivator for the patient. If they can see proof that they are progressing and getting better by doing the exercises, it will stimulate them to practice even more.

6 CONCLUSION

This study investigated the potential use of virtual reality applications in occupational therapy for stroke patients. The results of the study showed that the prototype created within the scope of this thesis was capable of assessing useful, correct, and detailed information about the execution and progress made in VR exercises, while offering a fun and satisfying game experience. The Meta Quest 2 VR glasses and controllers are suitable for building applications within this domain. Applications like this could be an added value to current stroke rehabilitation practices, by increasing patient motivation and offering objective progress assessment. Based on feedback from (occupational) therapists, we concluded that there is openness and demand for collaboration between care providers and engineers. They offered great insight into how our prototype application could be altered to make it even more usable and intuitive for patients, and showed great interest in the future of VR as an occupational rehabilitation tool.

ACKNOWLEDGEMENTS

We would like to express our sincere gratitude to all the people that contributed to the successful completion of this thesis.

First, we extend our greatest appreciation to our thesis promotor, Maria Torres Vega, for her support, guidance, and continuous encouragement throughout the development of our prototype and the writing process. Her insightful feedback and dedication to our project have been instrumental in shaping our work.

We would also like to thank our co-promotor, Carlos Rodriguez-Guerrero, for his valuable input, encouragement, and assistance in the development of our thesis. His expertise in the field and his guidance have been of great value.

Furthermore, we would like to express our appreciation to P. Wildiers and W. Habils. Their professional advice and feedback were crucial in shaping our understanding of the practical aspects and requirements of our project.

Last but not least, we would like to thank the people that contributed to the experimental phase of the thesis. Their assistance was greatly appreciated.

LIST OF SYMBOLS

BIBLIOGRAPHY

Agency for Healthcare Research and Quality (2010). Nasa task load index. `https://digital.ahrq.gov/health-it-tools-and-resources/evaluation-resources/workflow-assessment-health-it-toolkit/all-workflow-tools/nasa-task-load-index/`.

Balasubramanian, S. e. a. (2015). On the analysis of movement smoothness. *Journal of NeuroEngineering and Rehabilitation*, 12(112).

Berthier, N. E. and Keen, R. (2006). Development of reaching in infancy. *Experimental Brain Research*, 169:507–518.

Bestware (2022). Senseglove nova. `https://bestware.com/en/senseglove-nova.html`.

Brown, R. (2022). What is a stroke? a mayo clinic expert explains. `https://www.mayoclinic.org/diseases-conditions/stroke/symptoms-causes/syc-20350113`.

Caldas, O., Sanchez, Sanchez, N., Mauledoux, M., Avilés Sánchez, O., and Rodriguez-Guerrero, C. (2022). Leading presence-based strategies to manipulate user experience in virtual reality environments. *Virtual Reality*, 26.

Camardella, C., Chiaradia, D., Bortone, I.and Frisoli, A., and Leonardis, D. (2023). Introducing wearable haptics for rendering velocity feedback in vr serious games for neuro-rehabilitation of children. *Frontiers in Virtual Reality*, 3.

Carlijn Andrea Vernooij, M. L. and Reynolds, R. F. (2014). The complete frequency spectrum of physiological tremor can be recreated by broadband mechanical or electrical drive. *Journal of Neurophysiology*, 113:647–656.

Centers for Disease Control and Prevention (2023). Stroke facts. https://www.cdc.gov/stroke/facts.htm.

CNN Underscored (2023). Oculus quest 2 review: A great vr headset for the masses. https://edition.cnn.com/cnn-underscored/reviews/oculus-quest-2.

Doeringer, J. A. and Hogan, N. (1998). Intermittency in preplanned elbow movements persists in the absence of visual feedback. *Journal of Neurophysiology*, 80(4):1787–1799.

Flint Rehab (2022). Hand exercises for stroke patients. https://www.flintrehab.com/hand-exercises-for-stroke-patients/.

Gadgenda (2019). Noitom hi5 glove. https://www.gadgenda.com/hi5-glove-the-wireless-vr-glove-by-noitom.

Hilas, O. (2023). Stroke rates and hospitalizations. https://www.uspharmacist.com/article/stroke-rates-and-hospitalizations.

Hogan, N. and Sternad, D. (2009). Sensitivity of smoothness measures to movement duration, amplitude and arrests. *Journal of Motor Behavior*, 41(6):529–534.

Klimek, M. (2020). The future of healthcare is virtual. https://www.untitledkingdom.com/blog/oculus-quest-2-the-future-of-healthcare-and-medicine-is-bright-and-virtual.

Li, S., Liu, Y., Li, K., Cao, G., Li, S., Mao, Y., Wang, Y., Feng, J., and Tang, S.-t. (2023). Validation and effect of the nasa-tlx score on the assessment of the workload of pediatric robotic operations. *Surgical Endoscopy*.

Li, W. and Xu, D. (2021). Application of intelligent rehabilitation equipment in occupational therapy for enhancing upper limb function of patients in the whole phase of stroke. *Medicine in Novel Technology and Devices*, 12:100097.

Maskeliunas, R., Damaševičius, R., Raudonis, V., Adomavičienė, A., Raistenskis, J., and Griškevičius, J. (2023). A pareto-optimized system for assessing and recognizing hand movement to track rehabilitation progress. *Applied Sciences*, 13(9).

Neurolutions (2022). Activities to help improve motor skills and brain function. https://www.neurolutions.com/post/activities-to-help-improve-motor-skills-and-brain-function.

Pereira, M. F., Prahm, C., Kolbenschlag, J., Oliveira, E., and Rodrigues, N. F. (2020). Application of ar and vr in hand rehabilitation: A systematic review. *Journal of Biomedical Informatics*, 111:103584.

Perez-Cruzado, D., Merchán-Baeza, J. A., González-Sánchez, M., and Cuesta-Vargas, A. I. (2017). Systematic review of mirror therapy compared with conventional rehabilitation in upper extremity function in stroke survivors. *Australian Occupational Therapy Journal*, 64(2):91–112.

Roshanak Houmanfar, M. K. and Kulic, D. (2016). Movement analysis of rehabilitation exercises: Distance metrics for measuring patient progress. *IEEE SYSTEMS JOURNAL*, 10.

Rui Loureiro, C. C. and Harwin, W. (2004). *Robot aided therapy: challenges ahead for upper limb stroke rehabilitation*, pages 33–40. Proc. 5th Intl Conf. on Disability, Virtual Reality and Assoc. Technologies, Oxford, UK, 20-22 Sept. 2004.

World Stroke Organisation (2021). Learn about stroke. https://www.world-stroke.org/world-stroke-day-campaign/why-stroke-matters/learn-about-stroke.

Xie, H., Zhang, H., Liang, H., Fan, H., Zhou, J., Ambrose Lo, W. L., and Li, L. (2021). A novel glasses-free virtual reality rehabilitation system on improving upper limb motor function among patients with stroke: A feasibility pilot study. *Medicine in Novel Technology and Devices*, 11:100069.

Zhe Zhang, Qiang Fang, L. W. and Barrett, P. (2011). Template matching based motion classification for unsupervised post-stroke rehabilitation. *International Symposium on Bioelectronics and Bioinformations*.

Zhou, H. and Hu, H. (2005). Inertial motion tracking of human arm movements in stroke rehabilitation. *International Conference on Mechatronics Automation*.

KATHOLIEKE UNIVERSITEIT LEUVEN

APPENDIX A : DATA VISUALISATION PLATFORM EXAMPLE

Figure A.1: Example Training Progress Tab

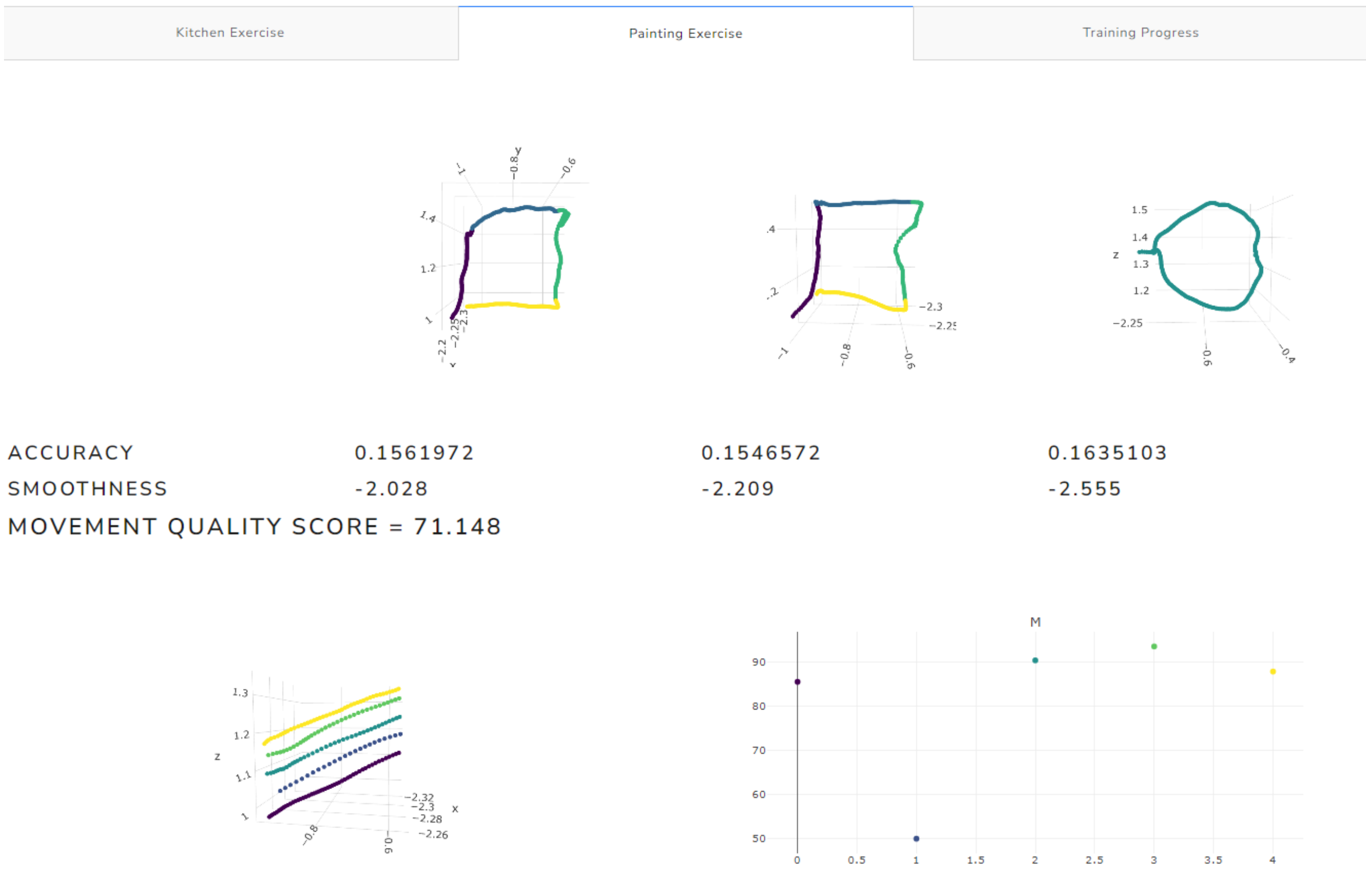

Figure A.2: Example Painting Exercise Tab

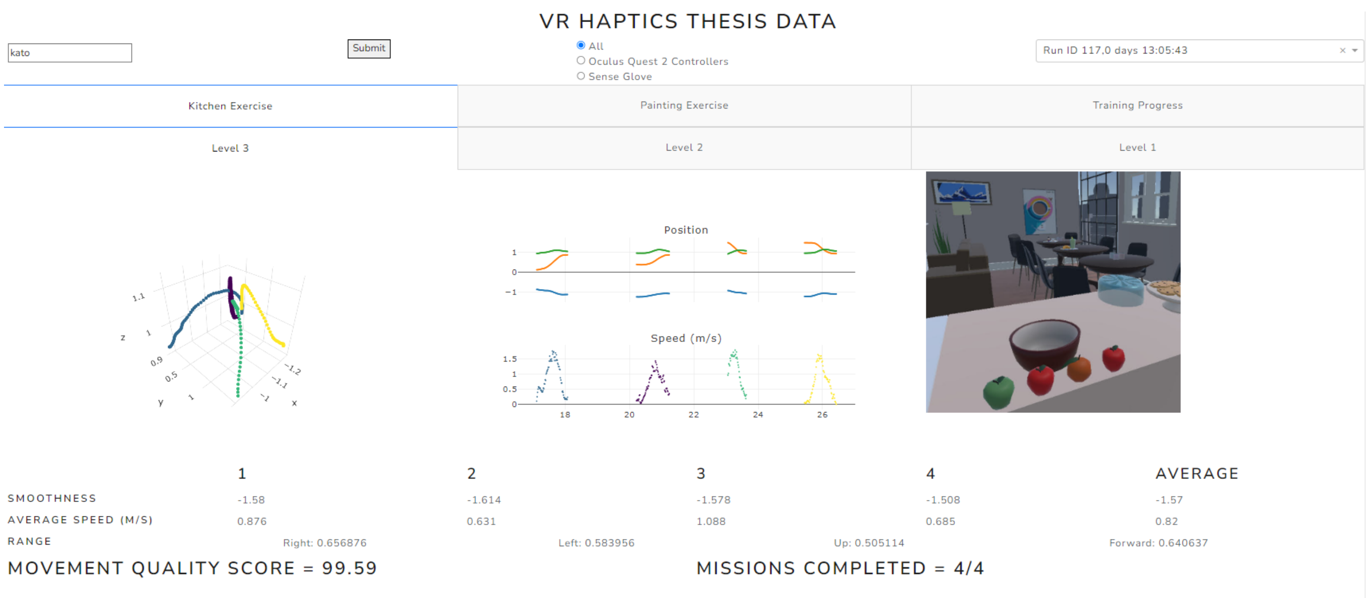

Figure A.3: Example Kitchen Exercise Tab

APPENDIX B : DATA INSERTION

```
public IEnumerator InsertData(float t, float xPosR, float yPosR, float zPosR, float xPosL, float yPosL, float zPosL, float rSpeed, float rAcc, float lSpeed, float lAcc)
{
    string dataBaseURL = "http://localhost/thesis/insertData.php";

    WWWForm form = new WWWForm();
    form.AddField("time", t.ToString());
    form.AddField("runID", GlobalVarManager.globalRunID);
    form.AddField("xPositionR", xPosR.ToString());
    form.AddField("yPositionR", yPosR.ToString());
    form.AddField("zPositionR", zPosR.ToString());
    form.AddField("rSpeed", rSpeed.ToString());
    form.AddField("rAcceleration", rAcc.ToString());

    form.AddField("xPositionL", xPosL.ToString());
    form.AddField("yPositionL", yPosL.ToString());
    form.AddField("zPositionL", zPosL.ToString());
    form.AddField("lSpeed", lSpeed.ToString());
    form.AddField("lAcceleration", lAcc.ToString());

    form.AddField("exerciseID", GlobalVarManager.exerciseID);
    form.AddField("tryID", GlobalVarManager.tryID);
    UnityWebRequest www = UnityWebRequest.Post(dataBaseURL, form);
    www.downloadHandler = new DownloadHandlerBuffer();

    yield return www.SendWebRequest();

    if (www.isNetworkError || www.isHttpError)
    {
        Debug.Log(www.error);
        Debug.Log(form.data);
    }
    else
    {
        // Debug.Log("Post request complete!" + " Response Code: " + www.responseCode);
        string responseText = www.downloadHandler.text;
        // Debug.Log("Response Text:" + responseText);
    }
}
```

Figure B.1: Function from registerMovement.cs, a Unity script. Contains step 1 of pushing data to database.

```php
<?php
    $servername = 'localhost';
    $s_username = 'haptics';
    $password = 'haptics1';
    $dbName = 'thesisdata';

    $time = $_POST["time"];
    $r_id = $_POST["runID"];
    $xPosR = $_POST["xPositionR"];
    $yPosR = $_POST["yPositionR"];
    $zPosR = $_POST["zPositionR"];
    $rSpeed = $_POST["rSpeed"];
    $rAcc = $_POST["rAcceleration"];

    $xPosL = $_POST["xPositionL"];
    $yPosL = $_POST["yPositionL"];
    $zPosL = $_POST["zPositionL"];
    $lSpeed = $_POST["lSpeed"];
    $lAcc = $_POST["lAcceleration"];

    $e_id = $_POST["exerciseID"];
    $t_id = $_POST["tryID"];

    $conn = new mysqli($servername, $s_username, $password, $dbName
        );
    if(!$conn){
        die("Connection Failed. ". mysqli_connect_error());
    }
    $sql = "INSERT INTO oculuscontroller (Time,runID,xPositionR,
        yPositionR,zPositionR,speedR,accelerationR,xPositionL,
        yPositionL,zPositionL,speedL,AccelerationL,exerciseID,tryID
        )
    VALUES ('".$time."','".$r_id."','".$xPosR."','".$yPosR."','".
        $zPosR."','".$rSpeed."','".$rAcc."','".$xPosL."','".$yPosL
        ."','".$zPosL."','".$lSpeed."','".$lAcc."','".$e_id."','".
        $t_id."')";
    $result = mysqli_query($conn, $sql);
    if(!result) echo "there was an error";
    else echo "Everything ok.";

?>
```

Figure B.2: Content of the insertData.php script.

APPENDIX C : HAPTIC TECHNOLOGIES

C.1 SenseGlove specifications

The SenseGlove Nova[1] is a glove that can track the fingers very precisely. It is developed by SenseGlove, a Dutch company that has been doing iterations on VR gloves for a while now. They claim that the Nova possesses the features required for VR training. The glove combines sensor-based finger tracking with computer vision hand tracking algorithms. These gloves also have a maximum refresh rate of 60Hz. The official SenseGlove website indicates the following specifications for these gloves.

Motion Capturing

The Nova gloves have a 9-axis absolute orientation sensor in the wrist. This sensor is a combination of a 3-axis acceleration sensor, a 3-axis gyroscope and a 3-axis geomagnetic sensor.

It also contains 4 sensors to capture the flexion and extension of the thumb, index, middle and ring finger. It offers force feedback with a max of 20N in flexion direction at the fingertips, so that digital objects can have a real hand presence.

Force Feedback

There are 4 proprietary passive force feedback modules that each deliver a maximum force of 20N in flexion direction at the fingertips. This force can be set in steps of 0.2N.

Haptic Feedback

It contains two Linear Resonance Actuators haptic motors of max 1.8G peak located at the fingertip of the thumb and index finger, and one voice coil haptic actuator with a sensitivity range of 45-250Hz, for impact simulation up to 4.3G, located in the palm hub of the SenseGlove Nova.

Figure C.1: SenseGlove Nova from Bestware (2022)

C.2 Hi5 gloves specifications

Noitom is a company dedicated to the development of motion capture systems for various fields. Not only do they have VR products, but also body motion capturing products that include bodysuits that measure precise and accurate

[1] https://www.senseglove.com/product/nova/

inertial motion data. The company is currently expanding into VR with products that allow complete immersion into VR environments. Their latest technology is the Hi5 VR glove[2]. It delivers wireless full-finger action with a series of IMU sensors that can accurately relay un-occluded motion data from glove to computer in real-time. The Hi5 VR Glove contains six, nine-axis IMU sensors on each finger for full left-and-right-hand motion capture with high-performance tracking. The gloves are lightweight and easy to put on, in contrast to the Senseglove Nova. They offer great documentation to develop within Unity, but are only compatible with the HTC Vive and Pico VR headset. As we decided to work with the Meta Quest 2 headset, we could not make a VR game with these controllers. However, they remain very performant and promising VR gloves.

Figure C.2: Noitom Hi5 gloves from Gadgenda (2019)

[2] https://www.noitom.com/hi5-vr-glove

APPENDIX D : OPEN QUESTIONS

D.1 Open Questions for healthy test subjects

- What did you think of the VR environment?
- Which aspects of the prototype do you think should remain, or worked out further, to make it more fun?
- Which aspects of the prototype do you think should be removed, or completely reworked?
- Do you think that further developing this would help motivate patients to continue their exer- cises?
- Are you interested in seeing your score and do you think that seeing progress will help motivate patients more

D.2 Open Questions for therapists

- What did you think of the VR environment?
- What do you think should be added to this prototype before it can actually be a product used in a hospital?
- Do you think it could help patients with motivation? And is patient motivation actually such a big problem?