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Masterarbeit

Developing a Multimodal Feedback Motion Guidance System in VR for People with Motion Disabilities

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Abstract

Motion is an important aspect in the area of physiotherapy. The correctness of those motions is even more important, especially in the home exercises. In this thesis, the prototype of a multimodal guidance system in virtual reality, which tracks the movements of the users and compares it to the correct position in the field of physiotherapy exercises was created. The get the requirements for the system, people who needed to go to physiotherapy, because of an injury or a disability (stroke, MS, NPC), were interviewed, as well as a physiotherapist. Based on the results, we have implemented a virtual physiotherapist and the auditory guidance as two modalities. Further modalities have been the ghostarm and the haptic guidance as vibration bands. The prototype in which the user can choose and combine the guidances have been developed. The system, the modalities and its limits have been evaluated in a online study and a pilot study, with the results, that until now the ghostarm and virtual physiotherapist are the most liked guidances. A user study is planned for the future.

Kurzfassung

Ein wichtiger Bereich in der Physiotherapie ist die Bewegung. Noch wichtiger, insbesondere bei Hausübungen, ist die korrekte Ausführung der Bewegungen. In dieser Arbeit wurde der Prototyp eines multimodalen Anleitungssystems in der VR entwickelt, welcher die Bewegungen der Benutzer verfolgt und diese mit Zielpositionen vergleicht. Um Anforderungen für das System zu bekommen, wurden Personen, die wegen Verletzungen oder Beeinträchtigungen (Schlaganfall, MS, NPC) in physiotherapeutischer Behandlung sind, genauso wie ein Physiotherapeut interviewt. Basierend auf diesen Ergebnissen haben wir einen virtuellen Physiotherapeuten, sowie die Sprachanleitung als zwei Modalitäten implementiert. Weitere Modalitäten sind der Ghostarm, ebenso die haptische Anleitung im Sinne von Vibrationsbändern. Entwickelt wurde ein Prototyp, in welchem der Benutzer zwischen den Anleitungen auswählen und diese auch kombinieren kann. Das System, die Modalitäten und die Limits wurden in einer Onlinestudie sowie einer Pilotstudie evaluiert. Der Ghostarm und der virtueller Physiotherapeut sind den Ergebnissen zufolge die beliebtesten Anleitungen. Eine Benutzerstudie ist für die Zukunft geplant.

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1 Introduction

The basic element for sports [CCCY16], dance [NTU+05] and also physiotherapy [TAT+14] is the learning of motions. Especially in the physiotherapy, the correctness of those motion are important to gain improvement or even to avoid injuries [TAT+14]. Many people see a physiotherapist during their lives. Most of them because of an injury, caused for example by an accident. Normally, they need treatment for a few weeks. This can extend up to the live-span, if the patients have a sickness (stroke [FCZ+11], Parkinson Disease [NDWD+01]) which leads to a motion disability. Those patients need a long-term rehabilitation. For some cases, for example Multiple Scleroses (MS) [Mur06], the physiotherapy is not used for improvement of the motion disability, but to prevent a worsening of the condition.

According to Wiesner [Wie17], due to restrictions of the health insurances, the physiotherapy sessions become shorter and there are less sessions, before the patients are on their own again. Furthermore, the author states, that a patient sees their therapist normally once in the week and is given homework exercises. An important aspect here is self-management. The patients must understand, how and why the specific exercises help them and how they can include the exercises into their every days life. A problem is that some patients do not do their daily exercises, because of a lack of motivation or because they are scared to do something wrong.

The goal of this master thesis is the investigation of possible feedback modalities of a system on users who regularly require physiotherapy. After requirements for such system are explored via literature and interviews, a prototype which implements suitable exercises with at least two feedback modalities is developed and evaluated.

For this, we have created a multimodal guidance system in virtual reality, which tracks the arm movements of the user and compares those movements to the correct poses. The prototype was built for the HTC VIVE and the VIVE controller. The first modality, the ghostarm, was chosen on the work of Yu et al. [YAM+20] in which they studied various visual arm guidances. In a physiotherapy session, the physiotherapist supports their patients with pushing them to the correct direction [BHT+14]. For this reason, we decided to use haptic guidance as our second modality. The usefulness of haptics as guidance has already been explored by inter alia [ASFH+17] [SFO+12] [NDGP14].

As explained in the work by Bennett et al. [BR19], empathy is a very important subject when someone is creating a system which is not meant for themselves. Therefore, we interviewed people which are currently in physiotherapy, as well as a physiotherapist to get requirements for the system. Despite from the system checking to correctness of their movements, every participant wanted a virtual physiotherapist who is explaining the exercises as guidance. This led us to the other two modalities for our system: a virtual physiotherapist and the auditory guidance.

We agreed on three exercises, for which a human 3D model we have used as the virtual physiotherapist was animated. For the auditory guidance, we recorded voice commands for every step of the exercises. The arms of the user as well as the arm of ghostarms were built with three spheres for the joints and two cylinders for the arm. The joints of the user's arms are connected with the VIVE trackers which positions are transmitted. Our colleagues from the LMU in Munich built the haptic devices and prepared the code for the micro controller for us. The vibration bands are meant to put onto the upper and forearm and consists beside the micro controller out of four vibration motors. Those motors can be activated separately with different strength to guide the user towards a direction. The communication to the application is over WiFi. The exercises are shown step by step, the next step triggered by a correct performance of the current step. Besides building a GUI in which amongst other things, the user can select the guidances they want to practice with and also combine those guidances, and including music, we prepared an algorithm which calculates the accuracy of the exercise.

Due to COVID-19, unfortunately, we were not able to conduct a user study to evaluate the guidances and our system. Nevertheless, we have conducted an online study, for which we recorded first-person-perspective videos surrounded by a SUS questionnaire, with both the participants from the previous interview and new participants. We evaluated the modalities against each other with the outcome, that there is no significant difference between them. But in the ranking, the participants liked the virtual physiotherapist most. A combination of multiple modalities was wished by many of them.

We also conducted a pilot-study with one of the supervisors. Although some technical problems, the participant was able to try out every modality. With the ghostarm and the virtual physiotherapist, she was able to do the exercises correctly. The auditory guidance led to the conclusion that it can not work, if the user does not know the exercise before. Unfortunately, the elastic bands of the haptic devices were transmitting the vibration, why the participant could not distinguish between the single motors and therefore, did not know in which direction the arm should be moved.

Both the online study and the pilot study showed the advantages and limits of this project. While things like the ghostarm are working very well, for the virtual physiotherapist and the auditory guidance the user needs some more feedback on the movements. Before a real user study can be conducted, some things must be changed, which are explained in Section 9.2.2.

2 Background

In this chapter, the background to this thesis is explained. Apart from virtual reality and its history, we take a closer look on haptics and physiotherapy.

2.1 Virtual Reality

The human being is perceiving the world over five senses: visual, auditory, olfactory, gustatory and tactile perception. In the year 1992, Heilig [Hei92] ranked the five senses by the order the human being is perceiving it (see Table 2.1) with the visual perception on top, followed by the auditory perception. This high priority of these two senses are used by Virtual Reality. VR surrounds the user with a synthetic world which can contain both real and non-real elements (including physical laws)[MTUK95]. In his book „The VR Book - Human-Centered Design for Virtual Reality“ Jerald [Jer15] defined VR as „a computer-generated digital environment that can be experienced and interacted with as if the environment were real.“ In this book, he also defines the term presence as the feeling of being there, not to be confused with immersion which is the degree of how well the user can interact with the environment, how well is everything visualized and how well the system responses autonomous to the users interactions [SW97]. A good immersion is also important to prevent VR sickness which is similar to motion sickness [LKK17].

Sense	Influence on the perception
Visual	70%
Auditory	20%
Olfactory	5%
Tactile	4%
Gustatory	1%

Table 2.1: Influence on the perception of the five senses

One of the first VR systems has been developed by Heilig in 1962 - the “Sensorama Simulator“ [Hei62]. This simulator consisted out of a chair on which the user would sit on and a big box with a window for the head. The system provided colored, 3D, moving pictures for the user, used even aromas, wind and vibrations. In 1987, the NASA developed one of the first Head-Mounted-Displays (HMD), which was controlled by the position, voice and gesture of the user [FMHR87]. In 2016, Oculus VR [1] released the first commercial VR HMD, followed by the HTC VIVE two months later [2]. In this thesis, we develop the system with the HTC VIVE Pro (see Section 5.1.1).

2.2 Haptics

Haptics is the perceptional system of the skin combined with the muscles, joints and tendons. Lederman and Klatzky [LK09] defined two subsystems of the haptic system: the "what" and the "where" system. The "what" system handles the perception and memory part, while the "where" system handles the guidance of action part.

In 1962, Seibel and Rochester [RN62] invented the keyboard glove to create a communication medium between the human and machine with a "relatively freedom of the hand". In the field of scientific visualization, Brooks et al. [BJOYBJK90] developed a haptic device to interact with displayed protein molecules.

In the field of VR, haptics are playing an important role. The users can interact with and manipulate objects, but it creates a greater presence, if the user is able to feel them, too. Hoppe et al. [HKK+19] created a system in virtual reality, in which drones are representing the object the user intends to touch.

In the area of guidance, haptics also become more and more important. To guide visual impaired people, Avila Soto et al. [ASFH+17] developed a system, in which a drone flies on front of a visual impaired person and guides it with auditory signals and haptic stimulus over a leash from the drone to the person.

In a physiotherapy session, when the physiotherapist shows new exercises and the patient makes mistakes by repeated them, the physiotherapist helps the patient by touching them towards the correct direction. This tactile guidance we want to use in our prototype with vibration bands.

2.3 Physiotherapy

A classical physiotherapy is divided into two parts: the sessions and the homework. Due to expensive costs and therefore, less sessions with a physiotherapist, the term of self-management get more and more important [Wie17]. It is important, that the patient is able to take care for themselves after the therapy. Because of that, the therapist must teach self-management to their patients. Self-management is split into three parts:

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[1] https://www.oculus.com/blog/first-look-at-the-rift-shipping-q1-2016/

[2] https://www.mobiflip.de/htc-vive-kommt-im-april-2016/

- Patient-education: The patients must understand how the problem and pain was caused, why the specific movements could help, what are the specific exercises are about and what the goal of them is.
- Ergonomic behavior: How can the patient change the environment (e. g. the working place) for a better pose / body behavior in the everyday life.
- Therapistic exercises: The physiotherapist must give the patient exercises, specifically for their suffering, to get better.

There are different reasons to see a physiotherapist. Some of them can be handled withing some sessions and weeks, like a broken leg, a torn ligament or tensions. Others need to be taken care of longer, months, years or even regularly throughout their lives. For example a Stroke requires a long treatment of rehabilitation [Par+12]. Patients suffering from neurological deceases (MS [Mur06], Huntington [AJ08], NPC [PG16] or ICP [Bob91]) have to get physiotherapeutic treatment for their life span and to prevent worsening of their condition. For people with motion disabilities, self-management is even more important, which we want to support with our prototype

3 Related Work

In this chapter, we discuss the work that is relevant for this thesis. At first, we discuss the efficiency of designs for people with motion disability, followed by MR-based systems. In addition to visual cues, diverse modality-based motion guidance, especially work relative to haptic guidance are mentioned.

3.1 Designs for People with Motion Disabilities

Because people with motion disabilities are the target users for our system, this system should address them. Furthermore, the efficiency of physiotherapy training at home is important to consider. Therefore, Chamberlain et al. [CCH82] made the study hospital exercises versus home exercises with the effect, that there is no difference between the study groups (hospital = Group A, home = Group B). Their participants had pain in the knees or even an osteoarthrosis. The treatment lasted twelve weeks with five times exercises each week. Despite there was no difference in the improvement between at home and in hospital, it needs to be mentioned, that the patients at home needed more proper instructions for their exercises.

Nieuwboer et al. [NDWD+01] also made a study about “the effect of a home physiotherapy program for persons with parkinson’s disease“. Their study was designed as a within-group study with at the beginning 39 participants, later 33 participants. First, there was a baseline period of six weeks, in which there was no physiotherapy at all, followed by a six week treatment and a three month follow-up period. In the hospital as well as at home, there was a significant improvement discovered already after the rehabilitation period. In the end, the functional activity scores at home have been twice as in the hospital, which the authors explained with three possible reasons:

- For the home treatment, the physiotherapists had a clear plan and treatment strategies.
- Limitations in a methodological way. In the hospital it was a blind scoring.
- A bias might have come up, because of the patients awareness of the test at home.

Empathy is a very important aspect, when a system for people with disabilities is developed. In their paper “The promise of empathy: Design, disability and knowing the Other “, Bennett et al. [BR19] described the importance of understanding the users of the product, especially in the case of disabilities. There are two ways of getting empathy into the system. One way is simulation. The developer simulates the disability while building and testing the system, for example covering the eyes to get empathy for blind people. The other way is asking disable people about their experiences and take that into account.

Because of the importance to get an insight into physiotherapy and the patients, we conducted an interview with physiotherapists and patients to get requirements for our prototype.

3.2 MR-based Motion Guidance Systems

Mixed Reality is often used for motion guidances, because of the possibilities of displaying any virtual objects. Furthermore, when videos are used to teach guidances, the user must translate the 2D motions into 3D. If the motion contains a rotation of the head or the body, the user is not able to see the display with the video on it anymore. Rotations can be taken into account with MR.

Dürr et al. [DWPR20] created a virtual reality system for motion guidances for music conducting. They used a virtual arm to show the exercises. Furthermore, they evaluated an abstract virtual arm against the human arm with the outcome, that there is no significant difference. An abstract virtual arm was also used in the project of Yu et al. [YAM+20]. The arm consisted out of three spheres for the joints and two cylinders representing the upper and forearm.

For our first modality, we got inspired by the project of Yu et al. and use the ghostarm, since Dürr et al. showed, that there is no significant difference in using an abstract arm or a human alike arm for motion guidances.

3.2.1 Sports

In the field of sports, various motion guidance systems already exist. He et al. [HCC+17] introduced a system for the Chinese martial art Taichiquan - better known as Tai Chi. The system was made for various environments, such as CAVE, HMD and PC. Both the motions of the teacher and the students are tracked for a collaborative motion learning. The basic Tai Chi motions were captured by 30 students to get a fundamental dataset. To track the motions, Microsoft Kinect was used. As in a real Tai Chi session, the teacher is displayed in the front. To be able the see also the side views, the students are surrounded by other displayed students, from which they can get the view.

Similar to this system, Wennrich et al. [WTK18] presented a virtual system for Karate Do katas (Karate forms for multiple invisible enemies). In this system, the student is surrounded by four teachers - one in the front, one left and right and one behind the student (see [RN62]). The movements of the students were tracked by a Kinect and displayed on a virtual avatar. To motivate the students, the kata teaching system was build as a game, in which the students can unlock belts and thus new katas.

Figure 3.1: Four karate teachers showing a kata. Students stand in the middle.

3.2.2 Motion Disabilities

A general VR system for physiotherapy was developed by Camporesi et al. [CKH13]. The physiotherapy process, consisting out of assigning exercises, let the patient do the exercises without supervision at home and the qualitative and quantitative evaluation of the progress is time consuming and the recovery takes longer. Therefore, the authors developed a system in which the patients and physiotherapists are connected, both's motions tracked and shown as avatars on a powerwall system. The physiotherapist can record exercises regarding to the patients needs and store them in a library. The motion tracking can be done by both Kinect cameras and Vicon cameras. Furthermore, the virtual avatars have two monitoring settings:

1. they can be visualized next to each other, or
2. they can be visualized onto to other, with the therapist's avatar semi-transparent.

The motions of the patients are measured and compared to the of the virtual physiotherapist and a visual feedback is provided. The physiotherapist can watch in real-time or record the movements of the patients for later analyzes.

The work of Camporesi et al. [CKH13] shows, that it is important to keep the physiotherapist in control. They must have access to the data of their patients to analyze the performance and possible improvements. Furthermore, they should be the ones setting the exercises for the patients. Therefore, we developed a further software for the physiotherapist to handle their patients, their performances and the exercises.

In their paper “Locomotor rehabilitation in a complex virtual environment“, Fung et al. [FMM+04] placed a treadmill for locomotor training into a virtual environment. With this system, especially people who were having a stroke can train their locomotor skills. The treadmill is a six-dof motorized motion platform. The virtual environment was shown on a large screen in front of the treadmill. To create realistic scenarios, different virtual scenes were created, both indoor and outdoor. The patients can walk in their own speed, but when they reach a specific speed, the system starts to challenge them by putting objects in the way, which the patient must walk around. During the training, the person is wearing a belt which is connected to the top of the treadmill to prevent the patient of falling.

In our prototype, we also want to use different difficulties to challenge the users. Therefore, it is possible for the user to set the difficulty in terms of distances towards the goal positions before starting the exercise.

Also for post-stroke rehabilitation, not relating to locomotor but the hand, Boian et al. [BSH+02] invented a virtual reality system with Gloves for the finger range, speed of motion and strength. They included gamification to the exercises such as scaring away a butterfly by closing the hand fast, or playing a small piano with four keys (one for each finger except the thumb). They evaluated their system with four stroke patients practising for three weeks, every day two hours. Every week the number of exercise repetition has been increased. Already after three weeks of exercising, a improvement in the finger speed and range could be shown.

The focus on making physiotherapy at home possible are having the authors of the paper“Physio@Home: Design Explorations to Support Movement Guidance“ [TAT+14]. First, they interviewed to physiotherapists to get some requirements for a physiotherapy system. The main findings have been:

- Feedback: The patients must get a feedback on their performance. Did they do everything correctly? Where are the mistakes?
- Feed-forward guidance: The patients must know what the next step of the exercise is.
- Mirroring: The patients must be able to see themselves. When they perform the exercise correctly, they know how it should look like.
- Self-pacing: The speed of how fast the patients are performing the exercise must be chosen by themselves - especially when they are injured.
- Simplicity: The visual guidance must be not too complex and easy to understand.

They used a screen integrated mirror to show the exercises with arrows and traces, both in 2D and 3D. For evaluation they have shown their system to the physiotherapists and colleagues. Both the arrows and the traces were easy to understand, but the 2D arrow caused issues with moving forward or backward, since it could not be differentiated anymore, if it is just a short arrow going upward or going forward. This did not occur with the traces, because of the different lengths during the path.

The findings from the interview of Tang et al.[TAT+14] are also very important for us. The users is able to see their arm as an abstract arm (mirroring), which they can move in their own speed (self-pacing), since the system waits for the next step, until the user do the current step correctly (feed-forward guidance, feedback). Those requirements, we want to extend with the requirements from our interview with the patients.

A survey on using the Nintendo Wii for rehabilitation was carried out by Fung et al. [FSP+10]. In their study, they used four Wii games for four different abilities: movement, balance, coordination and cognition. They have set the study in a rehabilitation hospital with physiotherapists and occupational therapists and let them play each game for 15 minutes. They agreed on the Wii is easy to set up and to use, and patients from the neurology, patients with trauma, and burn would benefit from playing the Wii games at home for their physiotherapy treatment. Furthermore a game motivates people to keep on exercising. Lange et al. [LRC+11] mentioned that still, the main goal for a game for rehabilitation must be the physiotherapy itself, while the game itself improve the motivation.

3.3 Diverse Modality-based Motion Guidance

Apart from MR-based motion guidance systems, other motion guidance system should be taken into account, especially haptic motion guidance systems, because they address to one more human sense. In this section, we primarily discuss work related to haptic guidance systems, followed by further systems tracking and recognizing the users motions.

3.3.1 Haptic Motion Guidance System

In addition to simulate visual cues in order to provide motion guidance, haptics can also play an additional role in this kind of systems, since they can increase user's feeling of presence, which is fundamental for the patients. In this context, we mention here some of the related work regarding haptics applied to immersive motion guidance systems.

Not in the field of physiotherapy or rehabilitation, but in the field of motion guidance, Schönauer et al. [SFO+12] created a multimodal guidance system with visual, vibrotactile and pneumatic guidance. The visual feedback is provided by arrows pointing in the direction of the correct pose in combination with a ghost avatar showing the correct position. Another variant of visual feedback they have used is a ghost avatar, marked in red overlapped with the current pose in white. For the vibrotactile feedback, there are twelve motors on the arm (three bands with each four motors). For better sensing, they used pulsed vibrations instead of continuous, at a frequency of 250 Hz. For the pneumatic feedback, they used a 3RD Space Vest around the chest, which put pressure on four actuators.

Chen et al. [CCCY16] developed a motion guidance sleeve as an external artificial muscles. Through muscle contraction, it can guide the forearm's internal and external rotation. The elastic sleeve is covering the complete forearm and parts of the upper arm. A virtual coach is giving the guidance through tactile feedback which can be changes by the motor speed. They have tested their system with two studies. The first study was to verify the clearness of the tactile feedback. They have tested 900 rpm versus 600 rpm with a significant difference towards the 900 rpm. In the second study, the participants should bring their arm in a specific angle by only following the contraction and relaxation of the external muscles. The participants were able to get the correct angle with a mean error within 3 degrees.

Also a sleeve but with combination of virtual reality was developed by Kapur et al. [KJB+10]. The correct movement is shown on a screen and the user tries to follow the movements. Their movements should be tracked by a full body suit with vibrotactile motors. The user is displayed as well on the screen and can see the differences of their movements compared to the master's. If the position is not close enough to be valid, the vibrotactiles give a signal, like a little push from the master. In their prototype, they have built a vibrotactile system for the arm. They are using three magnets for motion capturing (one on the shoulder, one on the elbow and one one the wrist) and six vibrotactile motors.

A hand motion guidance system with finger skin stretch has been tested by Norman et al. [NDGP14]. The finger skin stretch system was developed by Gleeson et al. [GHP10] and is a wireless device which has a little moving motor under the place where the finger is put on. By moving, the finger skin gets stretched. Norman and his team conducted a study about the ability to guide hand movements with this device. They decided for eight different motion cues and tested it at ten patients. After learning and training with the device, they needed to move their hand regarding the finger stretch towards the direction the device was showing. The participants could reach a high accuracy.

A vibrotactile sleeve was developed by Bark et al. [BHT+14]. Within this sleeve, there is a band with four vibrotactile motors. When the users did the exercise wrong, the regarding motors pushed them into to right direction. Because the physiotherapist also pushes the patient in the correct position and the high promises of haptic guidance, we use haptic device as the second modality in the prototype.

MusicGlove was created by Friedman et al. [FCZ+11] for especially people who had a stroke. Hand and finger training is important for stroke patients, but the motivation to train regularly gets lost after a while and the functions of the hands diminish. To keep the patients motivated, the author invented the MusicGlove. A glove which tracks the movements of the hand and fingers, and play notes and music. This is integrated into a game similar to Guitar Hero [Ars08], where colorful notes are falling down and the player needs the move the regarding finger to hit the note. The glove measures the number of correctly hit notes, and an average of how close the missing hits have been.

A completely different physiotherapy system than the others mentioned was developed by Fazekas et al. [FHT06]. This system works with a robot which leads the exercises of patients with spastic hemiparesis. Exercises for those patients have to be in a slow constant way and normally guided by a physiotherapist for about 20-30 minutes. The authors proclaim, that this could be done better with a robot. They used a unmodified industrial robot and added more safety systems to the robot:

- the robot's maximum speed is at 25 cm/s.
- the robot can only move when the patient is connected.
- an easy release mechanism has been installed in case of emergency.

The physiotherapist can record a new exercise with the robot and can edit things, for example the number of repetitions. Then the robot can repeat the exercise with the patients for the set repetitions. They tested their system with 12 participants over a 20 days trial, in total 240 training sessions. No dangerous situation occurred during this study.

3.3.2 Diverse Systems for Tracking Users

In 2015, Haas and his team [HPY+15] created a Kinect based system for physiotherapy at home. The system consists out of Microsofts depth camera Kinect which is connected to a tablet computer. There is a set of exercises implemented, which the computer shows and the Kinect is verifying the correctness of the exercises by caption the motion of the patients. If the exercise is executed wrongly, the tablet corrects the patient. The repetitions are counted, but only if the movements had been done correctly. The movements are recorded by the system and can be later analyzed by the physiotherapist.

Also using the Kinect, Cary et al. [CPG14] developed a rehabilitation system with an Artificial Neural Network (ANN) and a three tier server-client system. One client is the therapist analysing the data of the patients, and the other two clients are the supervised and unsupervised patients. Supervised means that the therapist is standing next to the patient and guiding the motions, whilst unsupervised is the patient at home. The therapist client and supervised client are connected to a server a the therapist's clinic. The unsupervised client is connected via internet to the clinic's server. The ANN consists out of two levels. The first level distinguish between left arm moving, right arm moving and both arms moving, while the second level is trained to tell the pose. Though the ANN is only made to distinguish between arm poses, it can be extended to e. g. leg poses.

A system which does not guide or correct the patients, but recognizes the exercises was introduced by Ar et al. [AA14]. The exercises consists out of three components: the motion pattern, the stance position - which means is the patient standing, sitting laying, etc. - and the existence of an object (e. g. a towel, a chair). With an Machine Learning algorithm (Bayesian Network) the system can distinguish between different exercises, including their components. The movements of the patients are recorded with an RGBD - camera (Red, Green, Blue, Depth) and because of the low costs, they used Kinect. Not only the exercises can be recognized by this system, but also the repetitions are counted.

Not only the recordings of the repetitions are important [AA14] [HPY+15] , but also displaying the repetitions for the user [BSH+02]. Therefore, we display the repetitions which need to be done in the exercise, as well as the repetitions which were already done. If the exercise contains sets of repetitions, the sets are displayed as well.

Inspired by the previous work, we built a system in VR, which guides the user multimodal. The ghostarm by Yu et al. [YAM+20] and a haptic device similar to Bark et al. [BHT+14] are the first two modalities in the system. To get an insight to physiotherapy and the requirements of the patients, we conducted an interview with physiotherapy patients.

4 Interview with Patients

As described in related work (see Chapter 3), empathy [BR19] is an important aspect for building a physiotherapy system for people with motion disabilities. It was important for us to include the requirements of both, the patients and physiotherapists. To gain the requirements, we carried out an interview which is described in detail in this section. All quotes in this section have been translated from German to English.

4.1 Preparation and execution of the Interview

Due to the times of COVID-19, we could not carry out the interview in person, nor just go to the physiotherapy offices and ask for participation. So, we used personal contacts as well as the social media website Facebook [1] in various groups. In the posts, it was explained that we want to build a physiotherapy system in Virtual Reality (VR) for physiotherapy at home, and that we want to carry out an interview to get the requirements of the patients. To find physiotherapists we contacted various physiotherapists via email. Then, we created a list of questions which covers questions about the participant's reason for physiotherapy, their motivation for the exercises which they need to do at home, as well as the features they would like to have in the system.

As soon as somebody wanted to participate, a form of consent which explains the interview and its goal, as well as the rights of the participant, was sent to be signed. In this consent form, the participant could decide, if they were fine with a record of the interview, so that we would not miss anything important. Also, a privacy form was sent to inform the participant about what how we handle their data. On an agreed date, the interview was executed via Webex [2], an online meeting portal.

After explaining shortly what the interview and the project is about, demographic data have been collected and the reason for the participant to see a physiotherapist was asked. Then, we talked about how often the participant sees their physiotherapist and how the sessions are built up. The next topic was the execution of the exercises at home: How often should they do their exercises at home? Are they doing the their exercises regularly and why/why not? The last and biggest topic was how they want the program to be. What should it look like? How should be guidance be like? Because most people automatically think of visual or textual guidance, we also asked for their opinion about haptic guidance.

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[1] https://www.facebook.com/

[2] https://unistuttgart.webex.com/webappng/sites/unistuttgart/meeting/home

At the end, we thanked them for participating and sent them a Thalia [3] giftcard for 5€ (if the interview lasted about 30 minutes) or 10€ (if the interview lasted about one hour) via email, which they needed to confirm as soon as they got it.

After the interview, the recordings were transcribed and deleted.

4.2 Results

In this section, the results of the interview is described. The section is split into the demographic data, the reasons of the participants to see the physiotherapist and their treatment, and their requirements for the system.

4.2.1 Demographic Data

In total, we interviewed seven physiotherapy patients. Three of them have been female and four male. The ages have been from 21 to 62 with an mean of 36.6 years and a standard deviation of 15.5. All of them were German native speakers but one. For this one, the interview was executed in English. All of them knew what VR is, three of them have worn VR glasses before.

4.2.2 Their Disabilities and Physiological Treatment

Four participants are seeing the physiotherapist because of an injury (knee, back, common), while one participant had a stroke. One is suffering from MS and one from Niemann Pick Typ C. The participant suffering from NPC attends to four session of therapy each week (twice physiotherapy, once ergo-therapy and once speech therapy) and therefore, does not need to do exercises at home. The stroke patient also does not do any physiotherapy at home, because they are scared of doing something wrong, but they go to therapy twice a week. The rest see their therapist once a week and get some homework for the rest of the week. They should do their home exercises daily for about 10-30 minutes.

We also asked them to be honest and tell us, if they are doing their exercises regularly. As said before, two of them do not do any exercises at all at home, out of the remaining five participants, three are doing their exercises regularly, while two are having a lack of motivation. We asked the three which are doing their exercises, why they are doing them. *"Because I can see improvements and I want to stay fit."* *"I think I am very disciplined, because I simply want my knee to heal. And I think, I understand that, if I don't do my exercises, nothing will improve."*, have been the answers.

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[3] https://www.thalia.de/

4.2.3 Requirements for our Application from the Patients Side

Motivation has been the intro question to our system. Clearly, we want to keep up the motivation of the patients to use the system permanently. The most mentioned thing was that there must be a check if the exercises are done correctly - either by the physiotherapists themselves or by the system automatically. Furthermore, a scoring is as important as the control. The patients want to see an improvement in their exercises. It is also important to know why the exercise is good for this specific injury and what it trains. Scoring, benefits and gamification also have been mentioned by multiple participants, as well as one participant wanted a reminder of the system via phone notification.

Presence is an important part of having a system in VR. The users should feel like they are being a part on the virtual reality and like they are really in it. Therefore, the environment of the system should look like the patients want it to look like. All of them but one want the environment be like in the physiotherapy office or a gym. The other participant wanted the environment be out side in the nature with some birds tweeting and calming music.

The most interesting part for us is to know, how the participants want their exercises been shown or guided. All of them wanted a virtual physiotherapist showing the exercises step by step and explaining the exercise. The physiotherapist also should explain about possible mistakes are and what it should feel like. Also, videos were often recommended, which show the exercises with an explanation. A counter with how many repetitions are left was required, too. One participant wanted a mirror which shows themselves as well as a correct ghost position. The misfitting point should be highlighted with colors. Corrections should be done actively by arrows showing in the direction and auditory (e. g. “lower your arms more“).

Further requirements for the system have been:

- The system should be easy to set up (plug ’n play)
- Instructions should be easy to understand and not too complex.
- The system should have a library of exercises and choose the fitting exercises for the sport / injury.
- The system should provide an assistant with whom they could interact (nice voice, know the patient).
- System should praise the patient, if the exercise was done well.
- It should be fun to train with the system (gamification).
- The security of personal data.
- A selection of the exercises as well as the modalities should be able.
- The physiotherapist should be able to see how often the exercises has been trained.
- After finishing the exercise, the pain/comfort with this exercise should be able to be rated (also visible for the physiotherapist).

- Music is an important aspect (also for motivation).
- The system should know, what the patient is physically able to do or not to do.
- Further information about the exercises should be displayed (which muscle groups does it train)

At the end, we also asked them, if they could imaging to be guided with haptic guidance. Most of them think that haptic guidance is hard to learn because of many patterns, while haptic feedback or correction could be working, since this is more less like getting pushed in the right direction by the physiotherapist. Two participants mentioned that they would like EMS more than haptic guidance.

4.3 Interview with the physiotherapist

The first big topic we have talked about was the exercises at home and the motivation of the patients. For the times of Corona, the physiotherapist uploads training videos online for his patients. The problem here is, that first, he can not control his patients, and even more important, many patients do not do the exercise correctly, when he is showing them in front of them, how should they be able to do their exercises correctly, when they only seeing it on a video. Furthermore, he is using the app Physitrack [4]. With this app, the physiotherapist is able to set a training program for his patients individually and if they forget what the exercise has been, a short video will show the exercise. A nice aspect of this app is, that the patients can rate their pain (1-10) while doing the exercise afterwards. If the rating is higher than seven, the app sends a notification to the physiotherapist. At this moments, the physiotherapist can start a video chat with the patients and can see the patient's performance on their exercise and corrects them.

Despite this, the patients always get some homework to do, and the physiotherapist notices immediately if they were doing their exercises or not. He said, that statistically 85% of all patients are did not do they exercises as often as they should do them, or not at all. Furthermore, he says that the most often used excuse is that they had pain or were scared of doing something wrong. *"(Doing something wrong) is totally overrated. ... It is better do it wrong than not at all. ... Repetition is the mother of skill."*

The regularity in doing their exercises of the patients differs a lot. The biggest gap is between athletes who want to return to their sports as fast as possible, and some old people who just want to get some massage. For the first group, it is often enough to have one or two doctor's prescriptions at max to make the patient healthy and sent them back to their sport, or even have the confidence that they can walk the rest of the way of recovery by their own. The second group bring one doctor's prescriptions after another and never really recover.

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[4] https://www.physitrack.com/

To motivate the patients, the physiotherapist said, was quite a difficult thing. For children it is more easy, they can be motivated with small rewards. For personal training, optic is the best motivation. He takes pictures of them in swimming suits at the beginning and after some months of training. Then the personal training customers can directly see the difference. And this keeps them motivated.

Gamification is also a big topic on how to motivate the patients. The physiotherapist mentioned multiple games he is already using in his session, e. g. using pagers shining in different colors and building up a parkour with them. Another example is a bike with big screens in the front showing tours of Tour de France[5] which the patients ride. A big thing which motivates a lot is music. But we should not use calm music, better rock music, loud, fast.

The next topic in the interview has been our system. What does the physiotherapist requires for it. He was explaining, that in the sessions, he explains first the exercise and then shows step by step and explaining again the steps and what important there. If somebody is not moving correctly, he pushes them a little. At this context we directly mentioned the haptic feedback. He said, that could be problematic for people having a paralysis or neurological diseases, since they might not sense the vibration well or even if, they might still not be able to move correctly.

As in the other interview, the physiotherapist said a virtual physiotherapist should show and explain the exercises and arrows should show into the direction the patient needs to move. But he said, that mirrors are a bad thing, since the patients always see themselves mirrored. They are moving their left arm and in the mirror they are moving their right arm. To show his patients themselves, he always records them.

As further requirements, he said, music would be a really important aspect for him. Also, at the beginning of the session there should be a board showing what exercises will be done in this session and at the end a scoring to show some improvements.

4.4 Takeaways from the Interview to the Application

In the previous described interview, the participants gave us a insight to their physiotherapy and their requirements for a guidance system. Two further modalities were given by the participants: the virtual physiotherapist and an auditory guidance.

As there is no real physiotherapist who verifies that the exercises are done correctly, the system must take over this part. For this, the system only shows the next step, when the current step was executed correctly. Furthermore, a statistic scene shows a graph about the accuracies of the session, because the participants required information about their progress and improvements.

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[5] https://www.letour.fr

An advantage of virtual reality is, that the developer can create the environment like they want. Therefore, we asked the participants, how the environment should look like. Most of them wanted the environment to be a gym. To create a good presence, the environment of the GUI is a physiotherapists reception, and for the actual training, the user is in a gym.

Because of physical movements limits, the system should know what the patient is able to do. In a separate application for the physiotherapist, therefore, the exercises are recorded with the patients and used as the goal positions for the main application.

To increase the motivation, it is possible to select, if there should be music playing in the background while practicing, as well as the exercises and the modalities are able to be selected by the user.

5 Design Aspects

5.1 Development Tools

5.1.1 Hardware

The hardware we are using in this project is the HTC VIVE Pro with its controller and the VIVE trackers (see Figure 5.1). The HTC VIVE Pro was realeased in April 2018 [1] and is the second HMD from HTC. The controller we are using to be able to interact with the GUI, while the trackers are used to track the movements of the arms.


(a) (b)

Figure 5.1: The hardware used for thesis a) The HTC VIVE VR glasses and the controller b) The VIVE trackers for the arms. On the left side the tracker for the shoulder, in the middle the tracker for the elbow and on the right side the tracker for the wrist

To be able to use the VR glasses, Steam VR must be installed, as well as the Lighthouse laser emitters must be put in place. At least two emitters must be in the room for tracking the glasses position. The emitters send laser stream in a horizontal and vertical way. Those to are alternating and the VR glasses in sensing them and calculates by the time it receives

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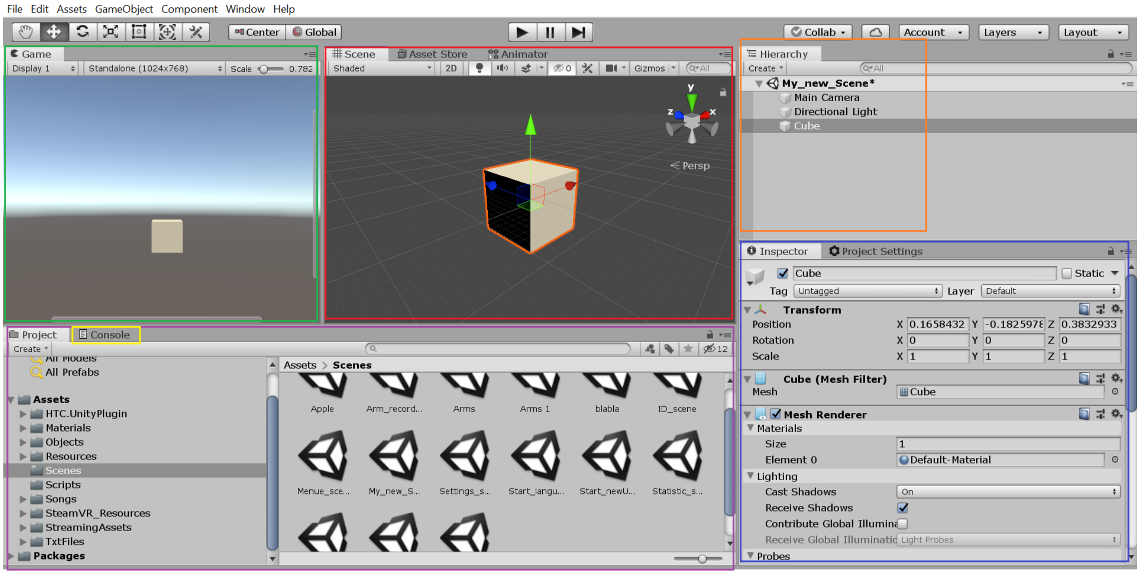
[1] https://www.pc-magazin.de/news/htc-vive-pro-release-preis-deutschland-kaufen-vorbestellen-3199177.html

the laser signals the position. The same the controllers and trackers are doing [NLL17] [BSC+18].

5.1.2 Unity

Unity 3D is an engine for primarily create video games which was released in June 2005 by Helgason, Ante and Francis [Haa14]. The engine is capable of graphics, audio, interaction, physics and even networking. Simple game objects can be created directly in Unity, as a cube, sphere, plane etc, more complex objects can be imported as e. g. obj-files or fbx-files. All objects can be manipulated by the translation, rotation and scale. To create scripts for code, either C or Java-Script can be used, but most of the users are using C.



☑ Cube ☐ Static
Tag Untagged Layer Default
Transform
Position X 0.1658432 Y -0.182597 Z 0.3832933
Rotation X 0 Y 0 Z 0
Scale X 1 Y 1 Z 1
Cube (Mesh Filter)
Mesh Cube
☑ Mesh Renderer
Materials
Size 1
Element 0 Default-Material
Lighting
Cast Shadows On
Receive Shadows ☑
Contribute Global Illumina ☐
Receive Global Illuminatic Light Probes
Probes

Figure 5.2: The Unity editor with the most important windows. Green: Game window, Red: Scene window, Orange: Hierarchy, Purple: Assets folder, Yellow: Console, Blue: Inspector

For Unity, there is an asset store, from which packages can be downloaded in integrated into the project. To be able to connect Unity with the HMD, the asset *Steam VR* from the Unity asset store is needed. Furthermore, we use the *VIVE Input Utility* asset for the trackers and the canvases in the GUI.

5.1.3 Autodesk Maya

Autodesk Maya which was firstly released in 1998 is a modelling and animation software [Woo14]. With this software, everything from a simple cube till a complex mesh like a human being can be modelled. In the Hypershape, materials and textures can be added to those models. Furthermore, models can be rigged and animated and, if wanted, a complete movie can be done with it.

For animations, it uses key frames, between which the differences of the positions are interpolated. With this, it is quite simple to animate objects by setting their transformation only in the key frames and the software automatically interpolates the transformation for in the frames in between.

In this thesis, we use Maya 2020 to build the office and training room of the system and some of their decorations. Also, we imported the rigged human model we are using for the virtual physiotherapist and animated the exercises by manipulating the joints (see Figure 5.3).

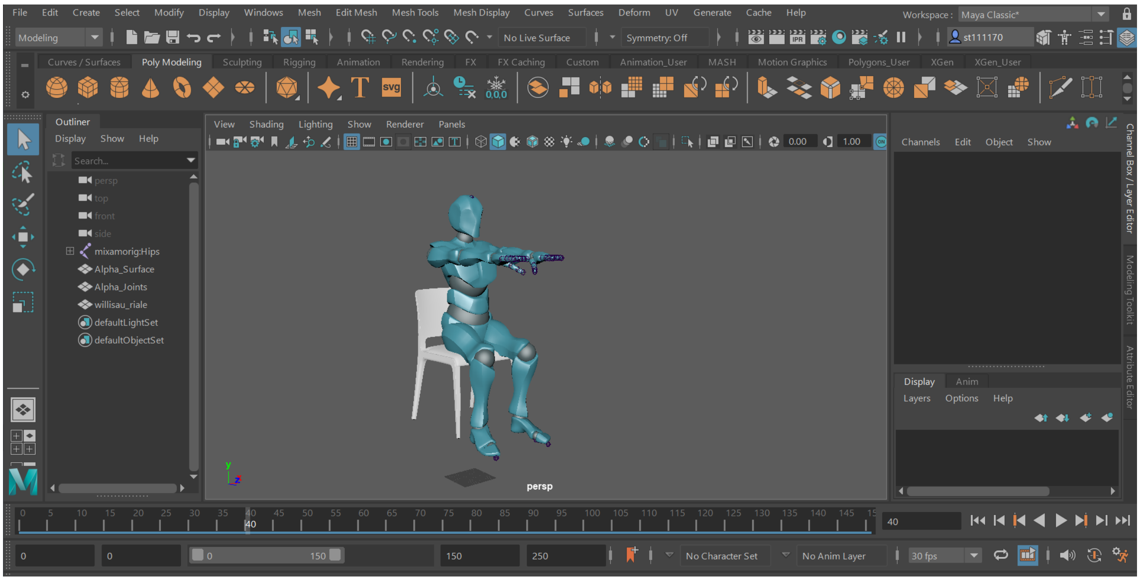


Figure 5.3: The model of the virtual physiotherapist in the Autodesk Maya 2020 environment.

5.1.4 Arduino

The open source platform Arduino is helping creating electronic object which can either stand alone or communicated with a computer. It is divided into two parts: The micro controller on which later the script from the second part, the Arduino IDE, is put. The code for the micro controller is written in either C or C++ and consists out of two parts: The setup-part and the loop-part. The loop-part is the part which is running the controller [BS14] [Bad14].

We are using Arduino to build and run the haptic devices we are using in this project. The vibration bands are playing the role of a server which receives message about the activation and strength of the motors over WiFi.

5.2 Exercises

For this prototype, we decided to focus on arm exercises which can be done in a sitting position. If there were some exercises with and some without a chair, the user would have to interact with an object which does not exist in the virtual reality. This might become dangerous. So, we needed to decide, if we want to do the exercises standing or sitting. We decided for sitting, because there are many people with motion disabilities who have problems with the balance or standing for a while. The VR environment could further worsen the balance and we do not want the users to hurt themselves. For the guidance system, all exercises start in the same pose with the arm straight in front of the body (see Figure 5.4). From this pose, the user goes to the exercise start pose.

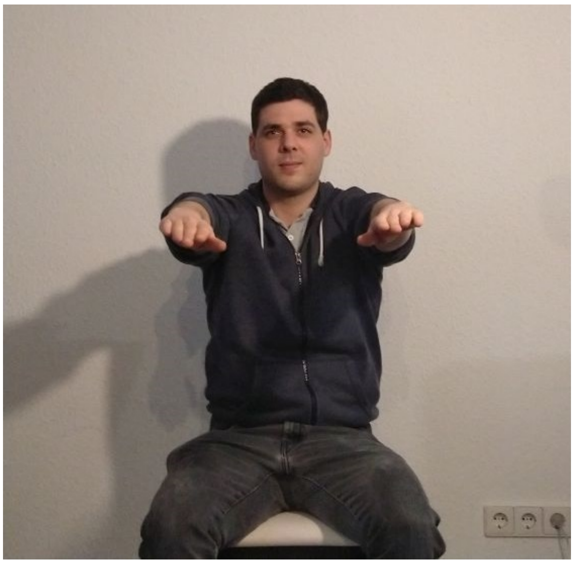
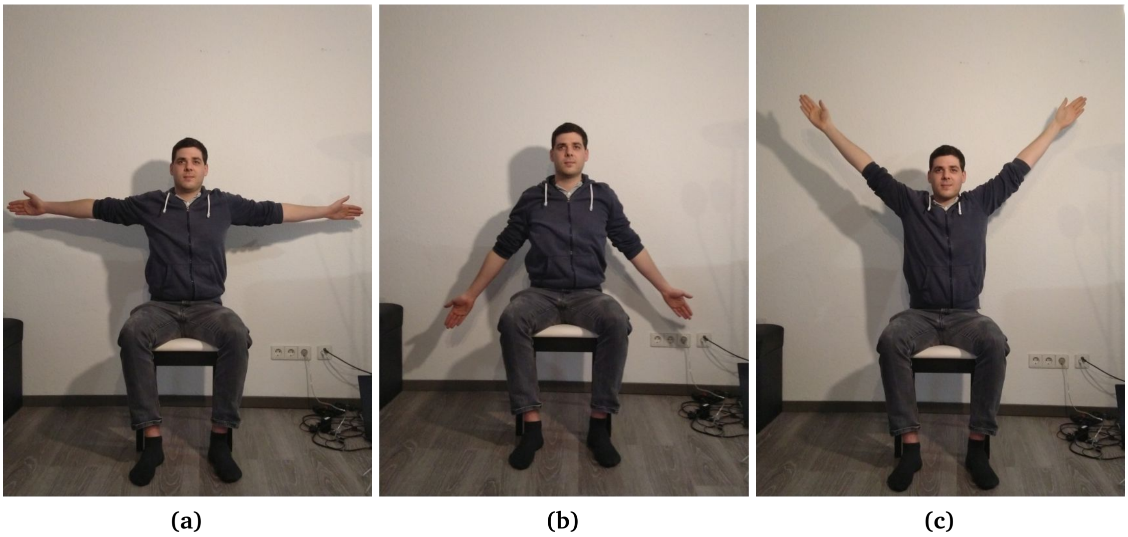


Figure 5.4: Start pose for all exercises

In the book "Übungen in der Physiotherapie" (Exercises in physiotherapy) by Renate Wiesner [Wie17], multiple exercises are described and supported with pictures. Out of this book, we took one of our three exercises: "Elevation in der Skapulaebene", which we renamed into "Wings ". In this exercise the user needs to put their arms straight to the side and slowly move them up and down (see Figure 5.5). This exercise can be done standing or sitting.



(a) (b) (c)

Figure 5.5: Wings-Exercise, b) and c) are looped. a) Wings start pose b) First step: Lowered arms c) Second step: Raised arms

The next exercise we took out of a Youtube video showing physiotherapy exercises for people suffering from MS [Mul20]. The first exercise shown is like picking apples. The start position is holding the arms in front of the chest, elbows pointing down and hands closed. Then one arm is raised into the air and the hand opens. Then the arms is took down again, while the other rises (see Figure 5.6). We showed the physiotherapist we interviewed the exercise and he mentioned, that in the prototype we need to take into account, that not everyone can put their arms up straight and they might make a hollow back to success the exercise. In that case the exercise would be useless or even worsen the patient's condition.

The last exercise we have have decided to include in our prototype was given by the physiotherapist. For this exercise the user needs their arms, but it is mainly made for the upper spine. In this exercise, the arms are horizontal in front of the chest, the hands upon each other. The upper body with the head locking forward is rotated left/right as much as possible (see Figure 5.7). It is important to keep the hips straight and not move them with the spine. Sitting on a chair prevents an accidental movement of the hips.

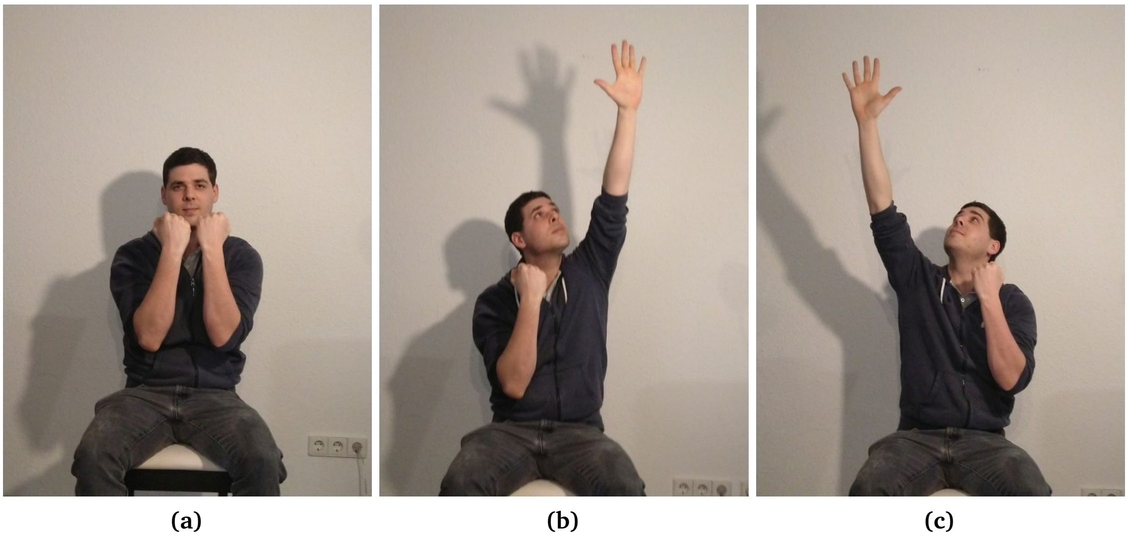


Figure 5.6: Apple-Exercise, b) and c) are looped. a) Apple start pose b) First step: One arm raised to the air. The hand is opened. c) Second step: Raised arm back in front of the chest, and other arm raised.

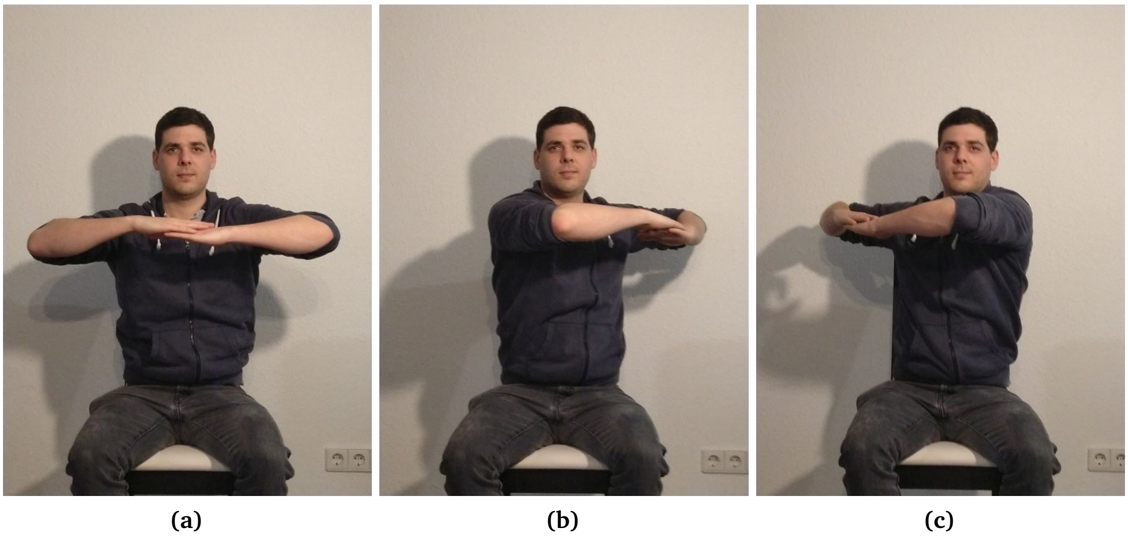


Figure 5.7: Spine-Exercise, b) and c) are looped. a) Spine start pose b) First step: Upper body with the arms moved to one side c) Second step: Upper body with the arms moved to the other side

5.3 System Usability Scale

In 1996, Brooke developed the System Usability Scale [Bro96]. With this scale the usability of a system or product can be measured. It consists out of ten statements, in which the participants need to rate the agreement from “strongly disagree “ to “strongly agree“. The statements of the SUS are:

- I think that I would like to use this system frequently.
- I found the system unnecessarily complex.
- I thought the system was easy to use.
- I think that I would need the support of a technical person to be able to use this system.
- I found the various functions in this system were well integrated.
- I thought there was too much inconsistency in this system.
- I would imagine that most people would learn to use this system very quickly.
- I found the system very cumbersome to use.
- I felt very confident using the system.
- I needed to learn a lot of things before I could get going with this system.

The rating is a Likert-Scale from 0 to 4. To get a result, the number are added up and lead to a value between 0 and 40. This value gets multiplied with 2.5 to increase the scale to 0 to 100. There are positive statements and negative statements, which are alternating. The negative statements need to be inversed first (subtracted from 4), before the usability score for the participant can be calculated [BKM08] [Lew18]. The higher the score, the more usable is the system.

6 Technical Design and Implementation

The physiotherapy for home treatment system consists out of two components: The main application in VR, which the patient uses and in which the VIVE trackers are used, and the application for the therapists to have control over their patients. In the following, the implementations of both applications is explained and shown.

6.1 Main Application

The main application is used by the patient. It was built with Unity Version 2019.2.12f (later with 2019.2.20f) and for the HTC VIVE glasses and trackers. Six trackers are used to record the movement of the patient for both arms (three trackers each arm). The application consists of a GUI for the user to control. To satisfy the requirements of the interview's participants, a physiotherapy office and a training room were built with Autodesk Maya 2020. To store the personal data, performance and settings, a file based database is integrated.

There are four guidance modalities developed: the auditory guidance, the haptic guidance, the virtual physiotherapist, and the posture guidance in the form of a ghostarm. They can be chosen single or in combination. Furthermore, the possibility to train with music, if wanted, is given.

6.1.1 GUI and Database

The GUI of the system is split into various scenes. All of those scenes use canvases with UI elements to interact with. Because the GUI should be usable for both the mouse and keyboard, and the VIVE, there are two canvases in each scene. The VIVE controller does not interact with a normal canvas. From the Unity asset store, the asset called *"VIVE Input Utility"* is used in the system and has an UGUI (Unity-GUI) example scene with a canvas. This canvas works for the controller, but not with the mouse. Therefore, two canvases are used in every scene: one for the VIVE controller, one for the mouse. The canvas of the mouse is disabled by default. In the first scene, the *ID_Scene* (see Figure 6.1a)), the user can press "k" for setting the mouse canvas active and the VIVE canvas inactive. Furthermore, in the *ID_Scene*, the user needs to enter the ID given by the physiotherapist in the physiotherapist application (see Section 6.2). If the user enters an ID which does not exists or does not enter anything at all, a warning text appears as soon as the user is clicking the continue-button.

After a valid ID has been entered and the continue-button has been pressed, the *menu_scene* (see Figure 6.2a)) appears. The name of the user, which the physiotherapist has set together with the ID, is read out of the name file in the user's folder and included in a greeting text. There are three buttons, the user can click from here on: the *Settings*-button (leads to the *settings_scene*, the *Training*-button (leads to the *training_scene*) and the *Statistic*-button (leads to the *statistic_scene*). If it is the first time, the user is logging in, the language will be set to English by default. If the user has already changed the language in the settings, the greeting text and the button names are in the language the user has selected. To set the names of the buttons and the greeting text, a script called *text_script* asks for the language from the *db_connector* which reads the language out of the corresponding file. The *text_script* uses public fields for the texts which can be dragged and dropped in those fields in the component. Because there are two canvases the public fields must had been doubled (one field for a particular text of the VIVE canvas, and one for the keyboard canvas). Furthermore, to prevent error, many if-parts must had been added to the script. To avoid unnecessary complexity, the *text_script* was doubled, the normal one and *text_script_keyboard*.

In the *settings_scene* (see Figure 6.1b)), there are again three buttons. One of the buttons leads to the *User_scene* (see Figure 6.1c)) in which the user can change their name. This username is private and not visible for the physiotherapist, but helps the system to become more personal and may increase the motivation of the users, since they can call themselves whatever they want to (e. g. superman). The other button leads to the *language_scene* (see Figure 6.1d)) in which the user can decide between English and German. Both scenes go back to the *settings_scene*. The third button is just a back-button back to the *menu_scene*.

The *statistic_scene* (see Figure 6.2c)) shows the accuracy of the previous training sessions in a plot. In dropdown menus, the user can select the exercise they want the data from, as well as if they want the plot being shown for both arms or only one of the arms. There is an update-button, which is currently calculating the accuracy for the training sessions which have been not calculated yet and saves them in a file. Due to large data sets, this takes a while to get finished. The algorithm for it is described in Section 6.1.7. Currently, the plot is created by an external plot.py python script, which creates images out of the accuracy data.

The last and most important GUI scene is the *training_scene* (see Figure 6.2b)). In this scene, in a dropdown, the exercise can be selected or, if wanted, all exercises can be selected. The exercises for this specific user are read from a file. The guidance can be chosen by toggles. The user can choose between the ghostarm, a virtual physiotherapist, auditory and haptic guidance. Of course, the user can also choose multiple guidances. A requirement of the participants in the interview was the possibility to listen to music while they are doing the exercises. From a license free homepage [1] four different songs have been downloaded (one song for each exercise and one for the all-exercise-selection). In a further toggle, music can be selected, as well as the volume can be adjusted in a slider. One

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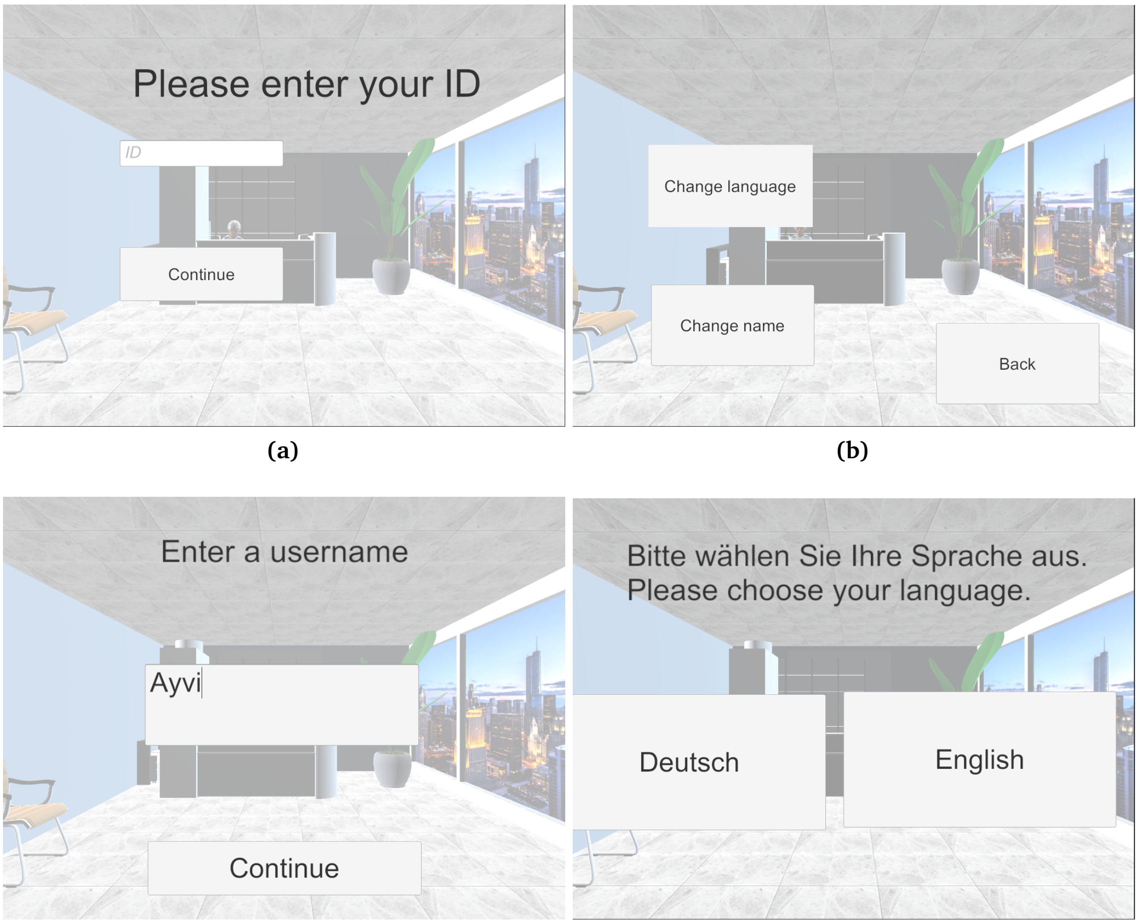
[1] https://www.bensound.com/



Ayvi

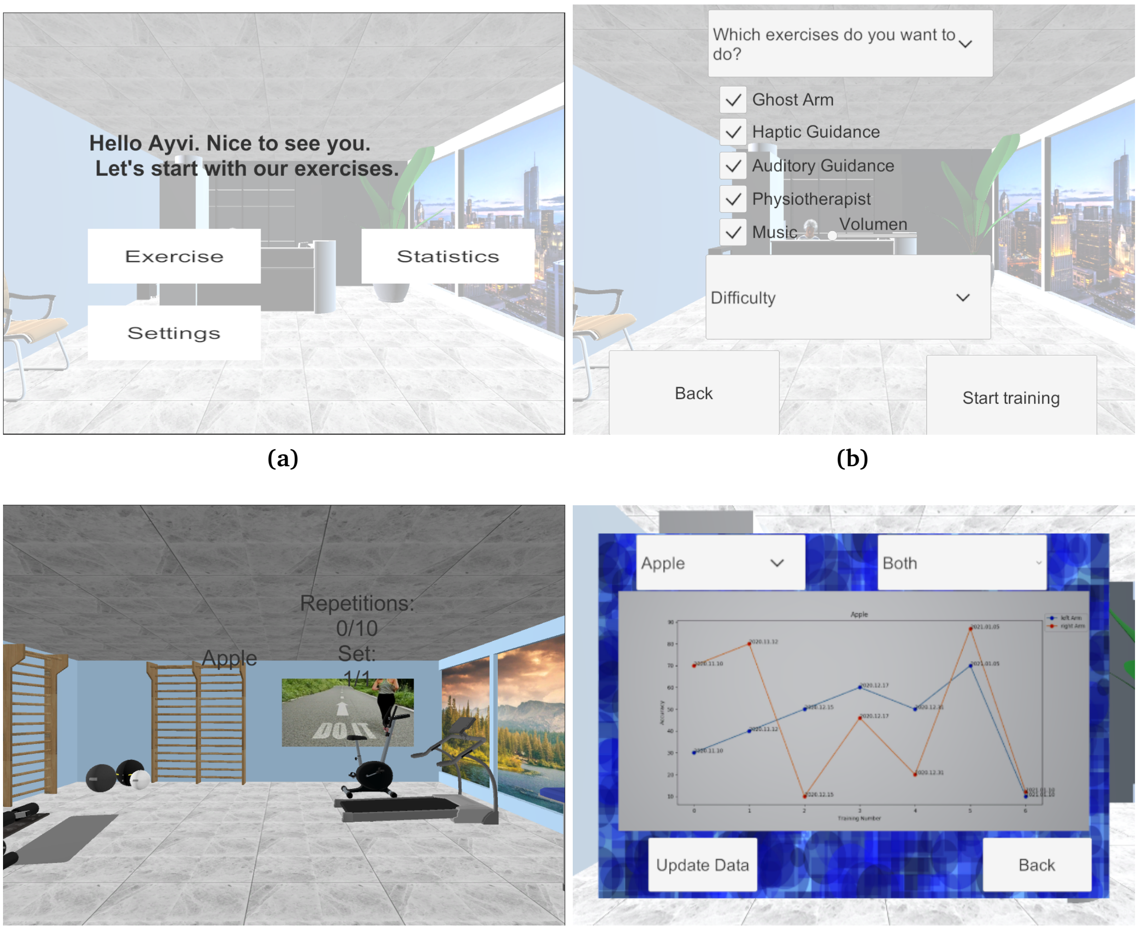
(a) (b)

(c) (d)

Figure 6.1: User settings of the GUI. a) The scene, in which the user enters the ID given by the physiotherapist. b) The setting scene. c) The scene in which the user can change their name. d) The language setting scene in which the language can be set to German and English.

of the four songs is playing while adjusting the volume. With another dropdown menu, the difficulty can be selected. With this selection, the threshold of the distance of the arm joints can be set to easy (15cm), middle (10cm) and hard (7cm). As soon as the start training button is clicked, the selected guidances, if music was selected and the volume, as well as the difficulty, is written into a file.

One small canvas is also added to the actual exercise scene (see Figure 6.2d)). This canvas is not interactively, but show the name of the current exercise, a countdown which shows when the exercise starts, as well as the repetitions (done and goal) and the sets (current and to reach) the physiotherapist has set for this exercise in their application. The repetition counts up, when a full movement is done, e. g. in the apple exercise both arms must have been up and down to finish one repetition. As soon as the repetitions are done, they are set to zero and the number of sets increases. Then, another countdown starts to give the user a rest. If the sets are also done, the scene changes back to the *training_scene* and the recordings of the arms (see Section 6.1.7) are written into the corresponding file.


Hello Ayvi. Nice to see you.
Let's start with our exercises.

Which exercises do you want to do?
☑ Ghost Arm
☑ Haptic Guidance
☑ Auditory Guidance
☑ Physiotherapist
☑ Music

(a) (b)

(c) (d)

Figure 6.2: Exercise settings, menu and statistic. a) Menu scene from which the user can guide to settings, training or statistic. b) Settings for the exercise. c) Canvas with repetitions and sets in the exercise scene. d) The statistic scene.

6.1.2 Environment

The system includes two different rooms. Because a requirement of the participants of the interview was, that the system should look like the physiotherapist's office and gym, we designed the rooms like that. The room around all the GUI scenes as build as a reception in an office. The room itself was build with Autodesk Maya 2020. One of the wall has a big window with a picture of a skyline in the background. The objects in the room have been downloaded from 3D objects homepages [2]. The room got decorated with plants, pictures

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[2] https://www.turbosquid.com/, https://www.cgtrader.com/

on the wall, waiting chairs and an reception desk. To bring some life into the room, an animated 3D human model has been downloaded [3] with the animation of typing on a keyboard (see Figure 6.3).

(a)

(b)

Figure 6.3: The environment of the GUI scenes built as a reception.

The training room consists basically out of the same room, with another picture for the window and the decoration is different. There are exercise equipment placed like dumbbells, kettlebells, a climbing frame, etc. (see Figure 6.4).

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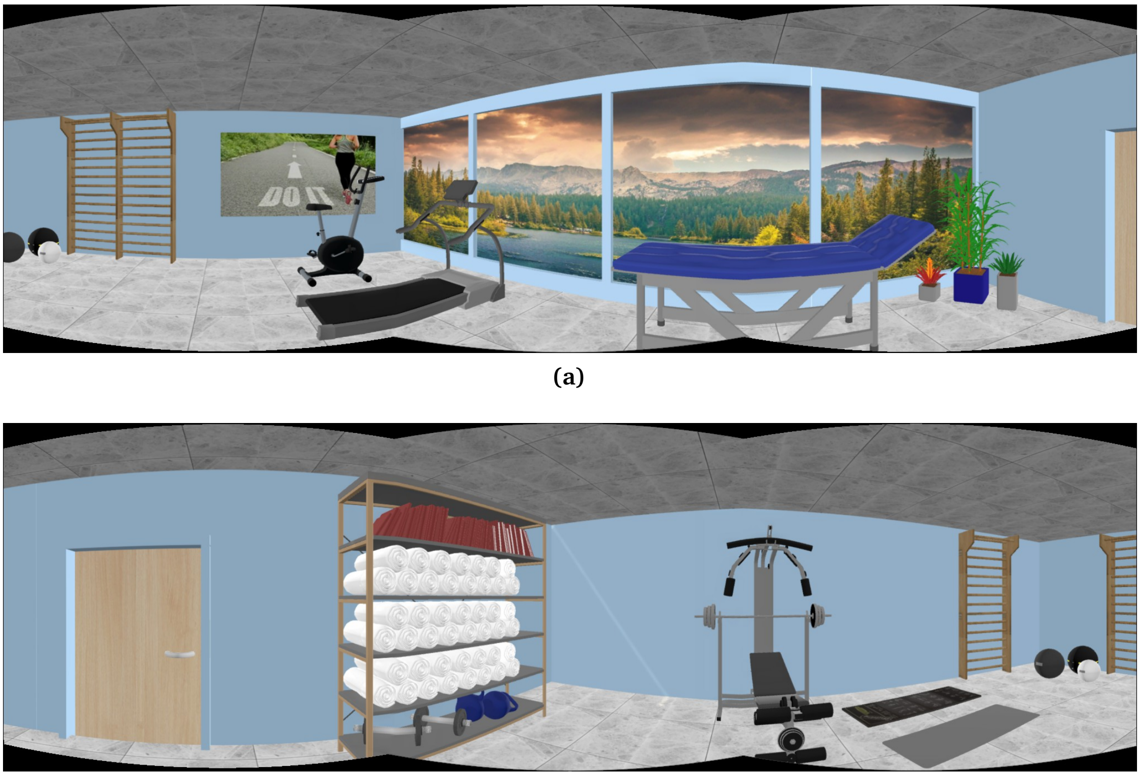
[3] https://www.mixamo.com/



(a)

(b)

Figure 6.4: The environment of the exercise scene built as a gym.

Due to the flexible position of the camera and the fix position of the room, it happened that the user was actually outside the room looking on a door, or even further away from the room. Therefore, the *position_of_room* script was created, which shifts the room always with the camera position:

$$room\_position = camera\_position + \begin{pmatrix} 0 \\ -1.3 \\ 3 \end{pmatrix} \tag{6.1}$$

The vector $(0, -1.3, 3)^T$ was chosen by trying and seemed to fit best.

To be able to see their own arms, an abstract arm mesh for the user has been created. One arm consists out of three spheres for shoulder, elbow and wrist, connected by a two cylinders. The spheres are colored in blue and green are the cylinders (see Figure 6.5). On the spheres from the asset *VIVE input utility* the component *VIVE Pose Tracker* was added. In this component the VIVE role can be set to various types like body role, device role, hand role and tracker role. Because we want to use the trackers for the joints, tracker role must be selected here. The second thing which must be set in the *VIVE Pose Tracker* component is which tracker is supposed to be connected to the joint. The Table 6.1 lists which tracker is put on which joint. It is important that the trackers are turned on in the order the tracker numbers are to make sure that e. g. tracker 1 is connected to the right shoulder joint.

Joint	Right	Left
Shoulder	Tracker 1	Tracker 4
Elbow	Tracker 2	Tracker 5
Wrist	Tracker 3	Tracker 6

Table 6.1: Tracker numbers for the joints

The upper and forearms are visualized by green cylinders. Those cylinders must be placed between the joints (shoulder and elbow for upper arm, and elbow and wrist for forearm), it should look towards the joints and the length should be flexible. To gain that, the script *transform_arm* calculates the position, the rotation and the length of the arm. The position is in the middle between the joints and calculated as in Equation (6.2). For the rotation, the *LookAt*-function is called and, because the short side was looking at the the joints, rotated by 90 degrees in x-direction. The x- and z- size of the arm was set to 10 cm. The y- size is calculated by the distance of the two joints and divided by 2, because the size is added to both sides of the pivot point (see Equation (6.3).

$$arm\_position = (Joint_1\_position + Joint_2\_position)/2 \tag{6.2}$$

$$arm\_length = \begin{pmatrix} 0.05 \\ |Joint_1 Joint_2|/2 \\ 0.05 \end{pmatrix} \tag{6.3}$$

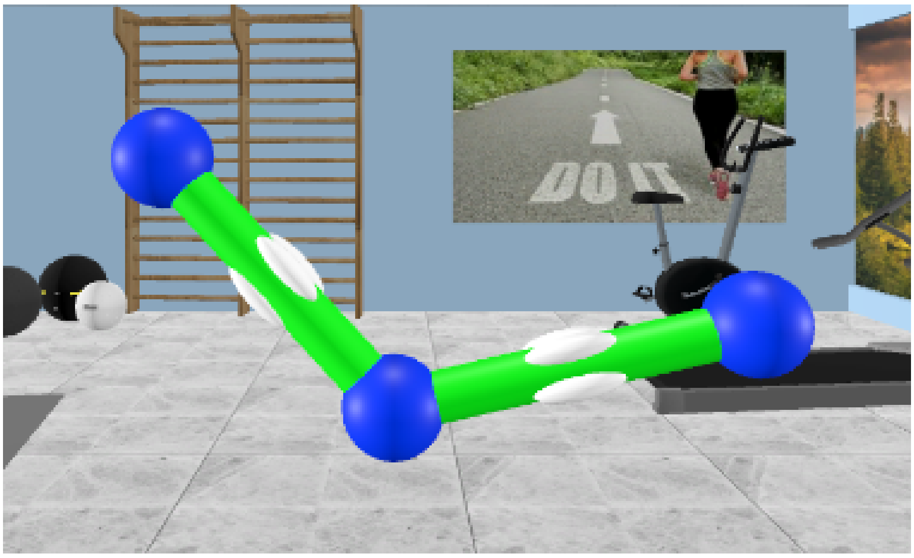


Figure 6.5: The visualization of the arm of the user. The blue spheres represent the joints (shoulder, elbow, wrist). The green cylinders are the upper and forearm. The white capsules are used for the representation of the vibrations.

6.1.3 Guidance by a Virtual Physiotherapist

In the interview, every participant wanted a virtual physiotherapist showing them the exercises. From the same homepage the receptionist was downloaded, we also downloaded another human alike model. This model should represent the virtual physiotherapist. The model was placed in front of the user on a chair. For each exercise, step by step animations have been created with Maya (see Figure 6.6). These animations were imported into Unity and each put into an animator controller.

To be able to handle the animators and the animation steps, the *animator*-script has been created. This script does not only handle the animator, but the whole guidance system. It takes care, that the correct guidances are shown / used, handles the repetitions and the exercises, if all exercises has been selected. While there is the countdown, the script gives the the animator an invalid controller and the virtual physiotherapist does not move. As soon as the countdown is down, the script asks the *db_connector* for the selected exercise and set the corresponding controller to the animator. Then the first step of the exercise is be played. The step is played once and waits for the command to continue with the next step. Since we do not know the repetitions for the exercises in advance and there are not as many animator steps provided, after the fourth step the third is shown and a loop of the steps three and four starts. If all exercises has been selected, the script asks the database, what exercises for the patient have been saved, and goes through all of them.

Because the virtual physiotherapist is not a child game object of the room, it needs to be shifted separately with the camera. The formula is the same as Equation (6.1) but the vector which is added differs, because the room and virtual physiotherapist have different pivot points. For the virtual physiotherapist the vector $(-0.255, -1.5, 3.45)^T$ is used to put it in a good position in front of the user.

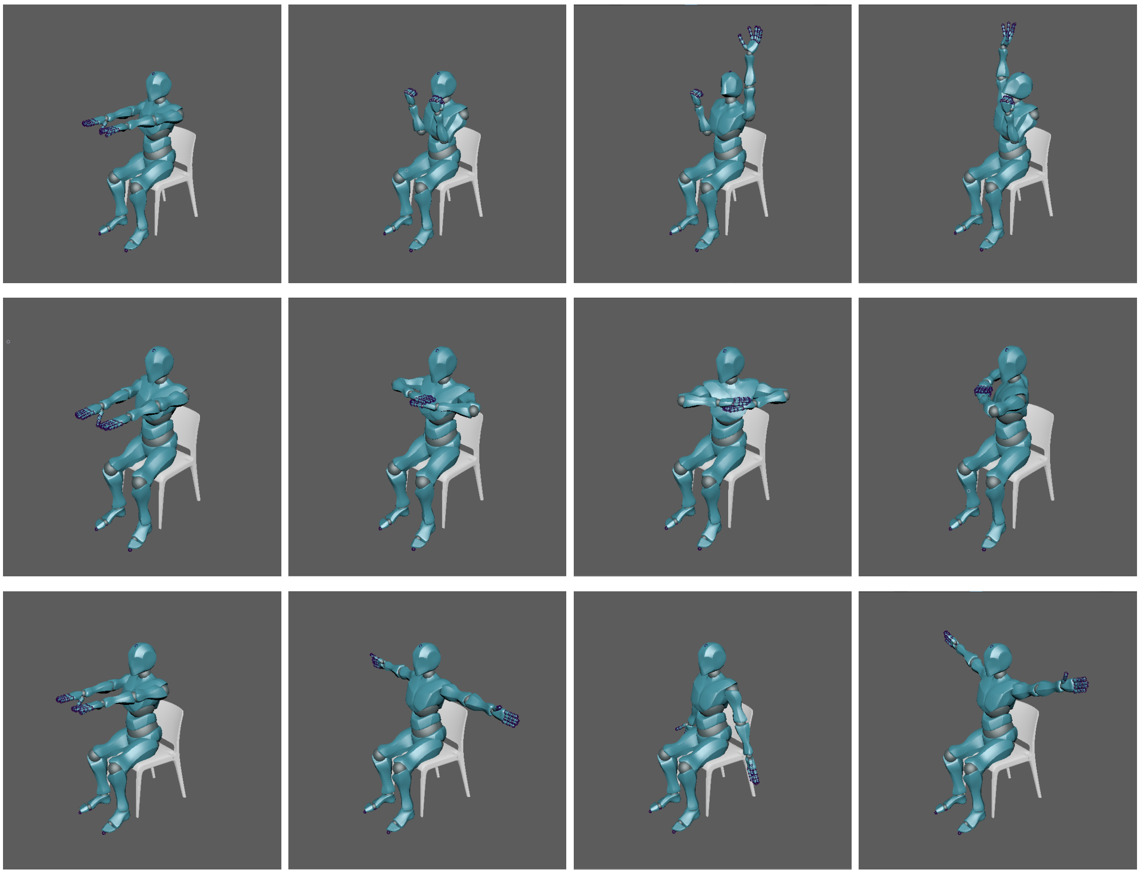


Figure 6.6: Animated exercises with the virtual physiotherapist. First picture in a row is the start pose. Third and fourth picture of each row loop. First row: Exercise Apple Second row: Exercise Spine Third row: Exercise Wings

6.1.4 Visual Guidance

In their paper “Perspective Matters: Design Implications for Motion Guidance in Mixed Reality“ Yu et al. [YAM+20] created different ways to guide a user visually. The streamer arm and the ghostarm has been evaluated. Because it was liked most by the users, we have decided to use that as our visual guidance as well.

The ghostarm is created the same as the user’s arm: three spheres for the joint and two cylinders for the upper- and forearm each arm. To get a visual difference between the ghostarm and the user’s arm, the joints of the ghostarm are colored in orange and the arms in red (see Figure 6.7).

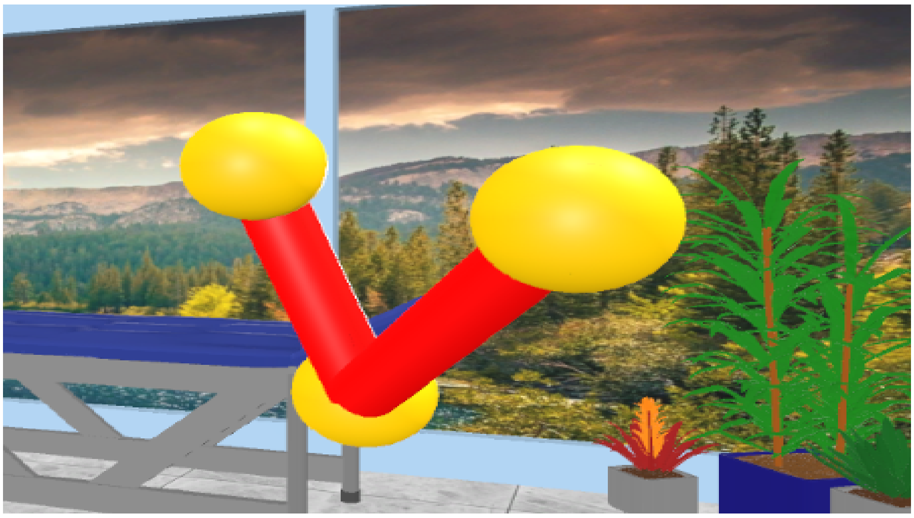


Figure 6.7: The ghostarm. The orange spheres represent the joints (shoulder, elbow, wrist). The red cylinders are the upper and forearm.

In the physiotherapist application (see Section 6.2), the user records the exercise once supervised by the physiotherapist. Those records are in the exercise's folder of the user. From those files (one for each joint and arm) the positions are read. This happens in the *reading* script for the right arm and in the *reading_left*-script for the left arm:

While the countdown is running, the *animator*-script sets the public bool move on false. The *reading*-script does not read and therefore, does not set the positions to the ghostarm. As soon as the countdown is down and there are no calculations of the *accuracy*-script (see Section 6.1.7), the reading starts. For every joint the corresponding file is read from the file and split in to it's steps. For our selection, every exercise consists out of four exercise steps, which are made visible in the files as „_“ . Afterwards, the step which is set by the *animator* is split in to it's single positions by splitting at the line end. Because in the physiotherapist system both position and rotation of the joints is recorded, this needs to be split as well. To be able to transform the position-string in to a position-vector and because a German system is used, the English float-dots must be replaced by the German float-commas. After this is done, the x-,y- and z-positions are extracted, transformed into floats and a new vector is built.

Unfortunately, we can not simply set those vectors as positions for the joints, because the user might be on another position in their environment as they have been in the physiotherapist's office. The ghostarm should appear close to the user's arm now, why for the first position in the first step, the ghostarm shoulder is set to the position of the user's arm shoulder. The elbow and the wrist positions are calculated by the vector pointing from the original shoulder position to the original elbow position added to the current shoulder position (wrist with the original elbow and wrist positions). For the further positions, the vectors from the original last positions to the original next position are added to the current positions.

6.1.5 Haptic Guidance

Because haptic devices are promising for motion guidance [CCCY16] [KJB+10] [NDGP14] [GHP10], we also decided to use haptic feedback and guidance in our prototype. To get an individual designed device, our colleagues from the LMU in Munich, Steeven Villa and Luke Haliburton, built four vibration bands (see Figure 6.8) and provided an Arduino script for those bands for us. The bands are meant to put each on the upper arms and forearms. Each band consists out of a micro controller with an micro usb port to transfer the Arduino script onto the controller, and four vibration motors. To be able to use the band wireless, a TCP socket connection over WIFI is prepared, as well as a slot for batteries. To let the motors vibrate, a JSON must be sent to the band, which looks like: {"motor1":0,"motor2":0,"motor3":0,"motor4":0}. The numbers behind the motor names represent the strength of the vibration from 0 to 255. It must be mentioned, that in a pre-study they found out, that a strength below 140 is not perceived by the user.

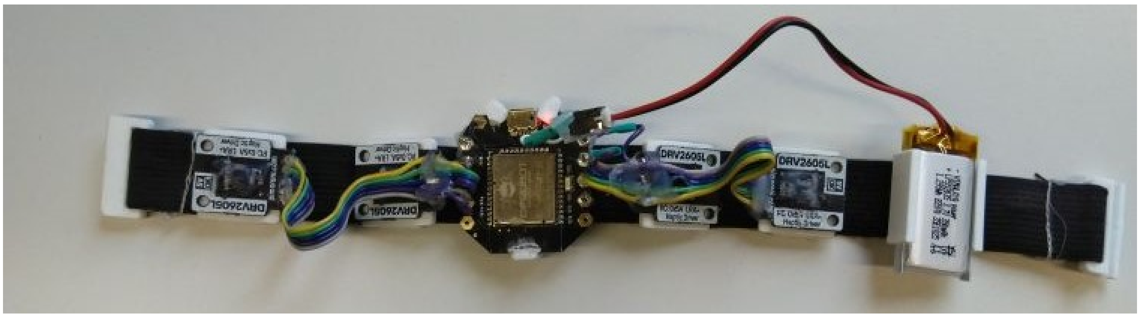


Figure 6.8: One of the four vibration bands. In the middle the micro controller is visible. On the left and right sides are each two vibration motors. The battery is placed on the right side.

To be able to upload the code from the Arduino IDE to the micro controller, the libraries *ArduinoJson*, *AnalogWrite for ESP32* and *Adafruit DRV2605 Driver Library* must be installed. The vibration bands act as servers inside the WiFi network, after it connected to the target network. After it also has set the LRAs (linear resonant activator) in PWM (pulse-width modulation) mode, it starts reading every incoming message and decodes it. If the message is a JSON in the correct format, it forwards the message to the motors via PWM.

To get the Unity software connected to the devices, the IPs of the bands must be read out with help of the Arduino script. Then, the IPs must be inserted in the *animator*-script in the start method. If haptic guidance was selected in the *training_scene*, the *animator*-script send the IPs and the port 8088 to the *vib_band*-script by calling the method socketConnect. In this script, four sockets for four bands are prepared. Because the *System.Net.Sockets* library can only sent binary or file messages, we decided to use a JSON file for each band with a string as wanted inside. So every time the vibration for a band changes, the JSON file get changed and is sent to the device. As soon as the training session is over, all four motors of each file are set to 0 and the vibration stops.

The most important thing here is to compute the vibration strength by the relational position of the user's arm towards the ghostarm. Our first approach for this was to compare the distances to the ghostarm of the opposite motors and let the closer one vibrate (see Figure 6.9). For this idea, the distance from the position of the ghostarm's upper arm to all vibration motors which are visualized as white capsule around the middle of the arms is computed. To also visualize the motors, the capsules are colored in red when they get activated, with a saturation (HSV-color) regarding to the strength. There is always a pair of capsules being at the opposite position of the user's arm. The capsule of a pair with the shorter distance to the goal position gets activated. If the distance is the same, no one them is activated. The strength is measured by the distance and gets lower the closer the upper arm gets to the ghostarm.

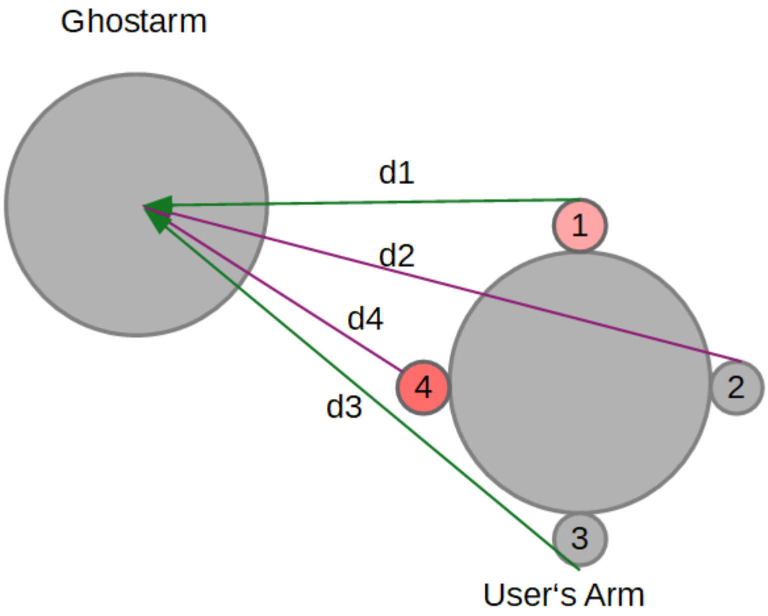


Figure 6.9: The algorithm of the first approach for the haptic activation and strength. Length of both purple arrows (opposite motors) are compared and the motor with the shorter distance to the ghost arm is activated. Same with the green arrows for the up and down arrows. Because the arm must move more to the left than up, motor 4 has a higher vibration strength than motor 1.

The forearm must be handled differently since it is depended on the position of the upper arm. For example, if the movements to go is only taking the arm to the side without changing the angle of the ell, there must be only done some movement of the upper arm, but not of the forearm, even there is a distance between the ghostarm's forearm and the user's forearm. To handle that, a further invisible ghostarm and the *up_low_calc*-script were created. This new ghostarm's upper arm is already at the position of the first ghostarm's upper arm, but the forearm is the the same angle as the user's forearm. The vibration strength is calculated for the forearm the same as fot the upper arm, but takes the distances between the ghostarms. So, in the previous example, the second ghostarm's forearm would be positioned perfectly in the forearm of the first ghostarm and therefore, would not set any vibrations.

This algorithm works fine for four motors, but we want to be flexible for all number of motors. Therefore, we needed to change the algorithm. In the second algorithm, the *up_low_calc*-script and the second ghostarm still exist and do the same thing as in the old algorithm, but the calculation of which motor's getting activated differs. First, the intersection of the vector from the ghostarm's upper- / forearm to the user's upper- / forearm with the user's upper- / forearm is computed. If the intersection is directly on a motor (on the visualization of a motor), this motor gets activated by 100%. If it is somewhere between two motors, both motors get activated with a strength relational to their distance to the intersection. To get the relational strength, at first the saturation value for coloring the red capsules is calculated in a range of 0 to 1 (see Equation (6.4), Figure 6.10. From this, the range is changed to 130 to 255 and the strength value is computed (see Equation (6.5)).

$$saturation_{capX} = 1 - \left(\frac{distance_{capX}}{distance_{cap1} + distance_{cap2}}\right) \tag{6.4}$$

$$vibStrength_{motorX} = (saturation_{capX} * (255 - 130)) + 130 \tag{6.5}$$

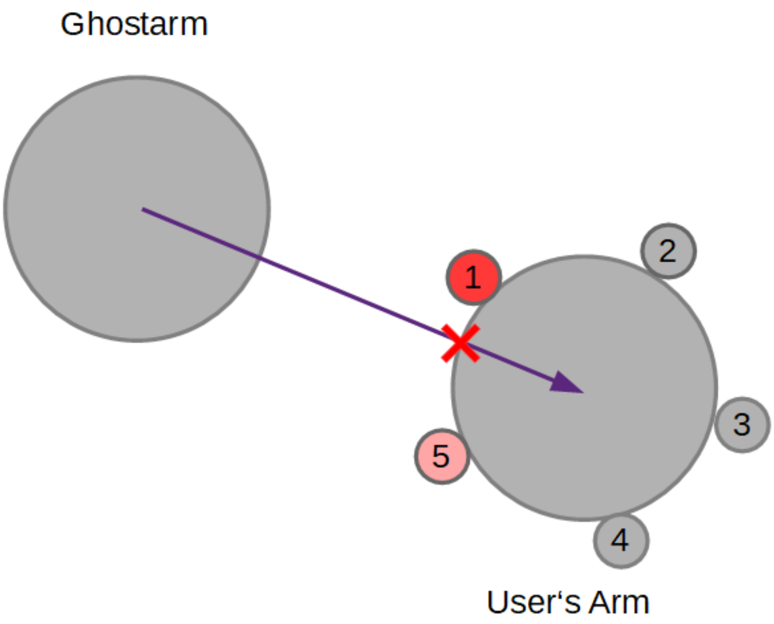


Figure 6.10: In the second approach which we used for the prototype, the vector between the ghostarm and the user's arm is the purple arrow. The intersection with the user's arm marked with a red X is between motor 1 and motor 5, but closer to motor 1. So the strength of motor 1 is higher than the strength of motor 5.

6.1.6 Auditory Guidance

Our fourth modality is the auditory guidance. In this guidance, only voices tell the user what to do. There are multiple text-to-speech assets in the Unity store, which all costs or supported only English speech. A working and free text-to-speech git repository was found[4], but the voice was very mechanical and not warm (what was a requirement of some participants in the interview). So, we have decided to record the commands and play them in Unity. As the background music, the voices are handled by the *source_manager*-script. First, it checks the selected language from the database to be able to give the instructions in the correct language. The *animator*-script starts the guidance when there is no countdown and tells the step and the exercise. Depending on the exercise and language, the *source_manager* takes the corresponding deposited audio clip as the clip of the audio.

The introductions for our exercises are as followed:

- Apple
    1. Get your arms back to your chest. The elbows should look downwards.
    2. Now, raise your right arm to the air. Open your hand.
    3. Get your arm back down. At the same time, raise your other arm into the air.
    4. Continue on doing that.
- Spine
    1. Get your hands in front of your chest. Put one hand over the other. The arms should be horizontal now.
    2. Without moving your arms, turn your spine to the right.
    3. Without moving your arms, turn your spine to the left
    4. Continue on doing that.
- Wings
    1. Open your arms straight to the side. Your palms should look forwards.
    2. Now, lower your arms.
    3. Raise them up again.
    4. Continue on doing that.

If there are more than only one sets, in the break between the two sets, a motivating speech will be given: “Now, take a deep breath and rest for a second, before we go on.“ Also, to keep the user motivated, in step 10 “Almost done. You’re doing a great job! “ is played.

---

[4] https://github.com/unitycoder/UnityRuntimeTextToSpeech

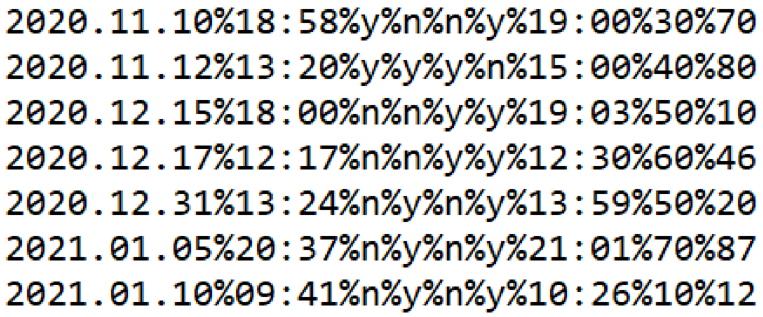
6.1.7 Accuracy

An important part of the system is to recognize, if the user is doing the exercise correctly. If the position of the arm is acceptable, the next step of the exercise is shown. In the *training_scene*, the user can select the difficulty from easy to hard. This selection sets the threshold of the maximal distances of the joint of the user's arm and joints of the ghostarm. Even if the ghostarm guidance has not been selected, the ghostarm is in the scene, but turned invisible by disable the renderer. For easy, the threshold is 15 cm, middle 10 cm and hard 7 cm. If the next step would be shown as soon as the shoulder, elbow and wrist of both arms are within this threshold, the error can never get below the thresholds. Therefore, the next step is hold up for 2 seconds, in which the user get the chance to get even closer to the ghostarm. Within this time, in the *check_if_valid*-script, an error is calculated as in Equation (6.6) for one update call. To not increase the error within every update call, a variable is counting the update call within the the 2 seconds. After the time is over, the error get divided by this variable to get a mean of all the errors within the time.

$$error = (error + (d_{sr} + d_{er} + d_{wr} + d_{sl} + d_{el} + d_{wl})/6) \tag{6.6}$$

Even more interesting than the knowledge about the error at the end position of a step is the error about the complete exercise. To get that, both the ghostarm and the user's arm are recorded the complete exercise and written into a file for each joint. If there are more than one sets, every set is written in to a separate file. Again, the steps are separated by a "_ " in the file. To prevent overwriting of the files and for the statistics, increasing numbers are at the beginning of the file name. The *record_movement*-script which is a component of the joints of all arms checks from the number 0 on, if a file already exists and counts them up, until the file does not exist. Then it creates new files for the joints and saves the positions and rotations in them. Furthermore, in the first line of the files, it writes the date on which the exercise was done, as well as the start and end time and the selected guidances. For the last, only "y " and "n " for each guidance are written. The order how they are written in the file is alphabetical: auditory guidance, haptic guidance, physiotherapist and visual guidance. The parts of the first line are divided by %. A first line for example looks like: "2021.01.22%18:58%y%n%n%y%19:00". Here, the exercise was on the 22.01., started at 18:58 (24h time), ended at 19:00. The auditory guidance and the ghostarm have been selected for this example.

In the *statistic_scene*, the user can click on the Update-data-button to get the accuracy out of the recorded files. This method automatically checks, for which of the recorded files the accuracy already have been computed, and calculates the missing accuracies (but maximal for ten new files). The in the next paragraph described algorithm runs through joint after joint, first of the right arm and then of the left arm, to get the accuracy for each joint. To get the accuracy for the arm, they are summed up and divided by 3. At the end, the accuracy is written in the *_acc.txt*-file in the folder of the exercise by the *db_connector* as a new line, which contains the first line of the recordings and the accuracies for both arms (see Figure 6.11).



```
2020.11.10%18:58%y%n%n%y%19:00%30%70
2020.11.12%13:20%y%y%y%n%15:00%40%80
2020.12.15%18:00%n%n%y%y%19:03%50%10
2020.12.17%12:17%n%n%y%y%12:30%60%46
2020.12.31%13:24%n%y%n%y%13:59%50%20
2021.01.05%20:37%n%y%n%y%21:01%70%87
2021.01.10%09:41%n%y%n%y%10:26%10%12
```

Figure 6.11: Example of the accuracy file. Every line represent a training session. % is the separator of the single data. First, the data and the start time is displayed, then which guidance has been selected (auditory, haptic, physiotherapist, ghostarm), then the end time of the session and the accuracies for both arms (left, right).

At first, the recorded joint file of the user's arm and the ghostarm is read and split into it's steps. Depending on the repetitions, the number of steps vary a lot. Hence, we are just interested in the original four steps and therefore, for the repeated steps (step 3 and 4) we calculate the mean error. To get the error of one step, through the list of ghostarm positions is looped and the smallest distance to any of the positions of the user's arm is set as the error for this particular position. This goes on for all positions and the mean of them is the error of the step (see Equation (6.7)). The last step is the transformation from the errors to an actual accuracy. A accuracy can be between 0 and 100. 100 if the mean distance is 0. For the 0 accuracy, a threshold distance can be set in the Unity editor. Twice the threshold as set in the exercise is a good threshold to start with. The accuracy is computed out of the error as in Equation (6.8)).

$$steperror = \frac{\sum^{GhostArm}\sum^{User} Min||Position_{User} - Position_{GhostArm}||}{n_{GhostArm}} \tag{6.7}$$

$$accuracy = 100 - (\frac{100}{threshold} \cdot error) \tag{6.8}$$

In the python script *plot.py* in the project folder, the plots for the *statistic_scene* are created. For this, the exercise _acc file of the user is read line by line. On the x-axis, the number of the session is put, while on the y-axis the accuracies of the right and left arms are plotted with the colors blue and orange. At the markers, the date of the exercise is displayed. It must be mentioned, that this way of displaying the data is just temporary and will be changed in the future.

6.2 Software for the Physiotherapist

Even though the main part of this thesis is to develop a prototype for a physiotherapy motion guidance system at home, it is important to include the physiotherapists themselves.

They need to set the exercises for their patients as well as see problems and improvements the patients are having with the system. It is important for the system that the patients movements are recorded and used as goal movements in the system. Furthermore, the recording should be supervised by the physiotherapist.

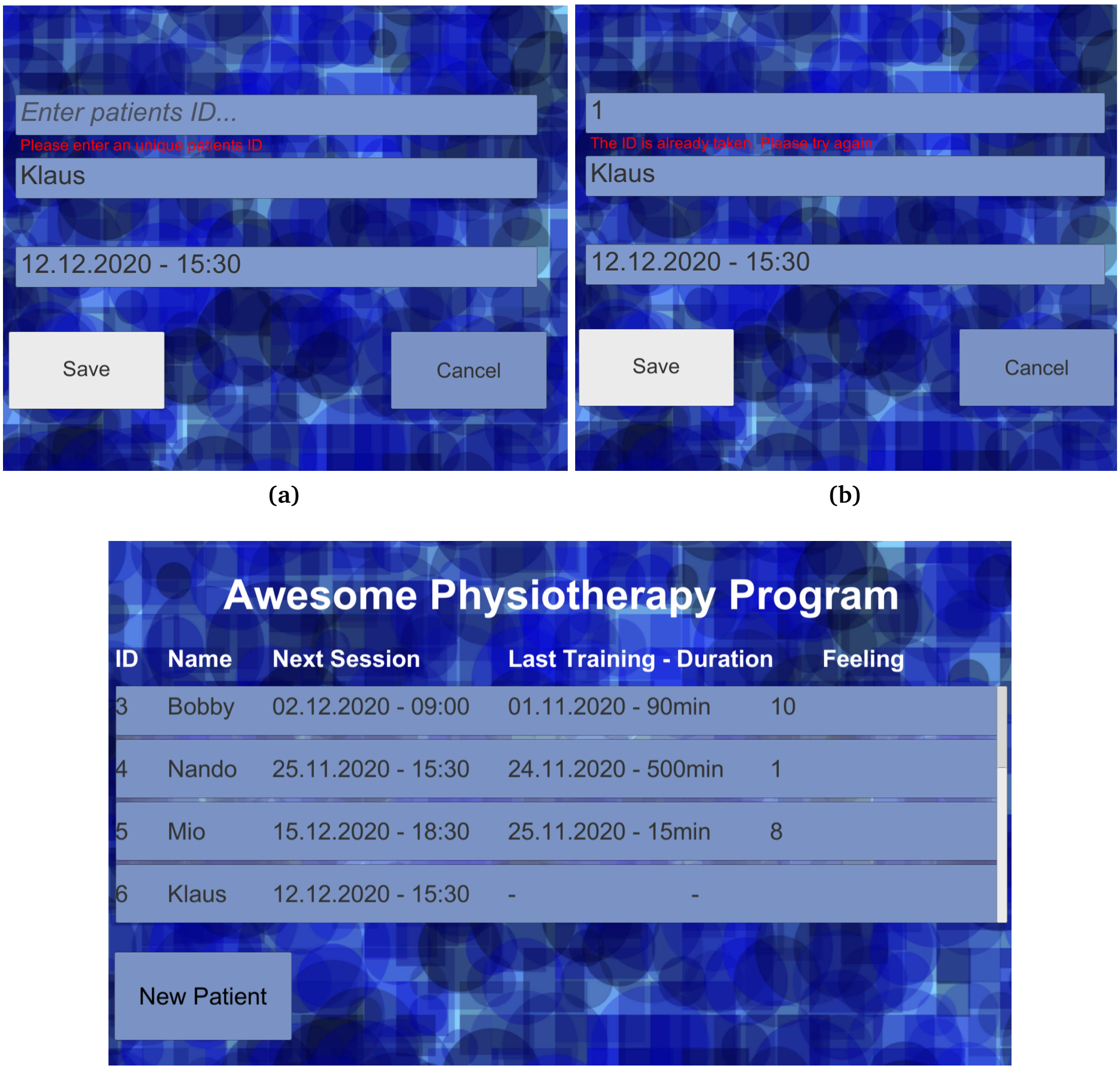
6.2.1 GUI and Database

The application consists out of five different scenes: *StartScene*, *newPatientScene*, *PatientScene*, *RecordScene* and *StatisticScene*. The application opens with the *StartScene* (see Figure 6.12), in which all registered patients are listed in a list of buttons. The ID, name, the next therapy session, the last training date and duration, and the feeling at the last training are displayed on the buttons. If there are no last training and therefore, no feelings yet, a “-“ is shown. A button to add a new patient is on the left bottom side of the screen.

ID	Name	Next Session	Last Training - Duration	Feeling
1	Ayven	26.11.2020 - 15:30	20.11.2020 - 35min	5
2	Enja	30.11.2020 - 10:45	25.11.2020 - 10min	8
3	Bobby	02.12.2020 - 09:00	01.11.2020 - 90min	10
4	Nando	25.11.2020 - 15:30	24.11.2020 - 500min	1

Figure 6.12: Start scene of the physiotherapist’s application. All patients are listed with further information. From here, by clicking on the patients name, the patient’s scenes opens. A new patient can be added by clicking on the new patient button.

If the new-patient-button is pressed, the *SceneManager* opens the *newPatientScene*. In this scene, the physiotherapist can set a unique identification number for the patient (see Figure 6.13). The number must be unique, because once a new patient is added, a folder with this number is created and all data regarding to the patient is saved within this folder. The id-number can not be changed later on. As soon as the physiotherapist is pressing the save button, the application checks, if the id-number already is used and if, a red warning text appears. A similar text appears, if the save button is pressed without any input in the id-field.



Enter patients ID...

Please enter an unique patients ID

Klaus

12.12.2020 - 15:30

(a)

1

The ID is already taken. Please try again

Klaus

12.12.2020 - 15:30

(b)

Awesome Physiotherapy Program

ID	Name	Next Session	Last Training - Duration	Feeling
3	Bobby	02.12.2020 - 09:00	01.11.2020 - 90min	10
4	Nando	25.11.2020 - 15:30	24.11.2020 - 500min	1
5	Mio	15.12.2020 - 18:30	25.11.2020 - 15min	8
6	Klaus	12.12.2020 - 15:30	-	-

(c)

Figure 6.13: New patient scene of the physiotherapist application. a) Warning text, when no ID has been entered. b) Warning text, when a ID which is already taken has been entered. c) A new patient has been added to the patients overview

Beside the id-number, the physiotherapist can enter the name of the patient as well as the next therapy session. These can be changed. As mentioned in the Section 6.1, the patients can change their names in the main application, but this does not affect the name in this application.

When everything is entered, the physiotherapist can press the save button. By pressing this, a folder called like the id-number is created, as well a exercise.txt - file within this folder. Also, the list with all patients is updated with the new patient and the *StartScene* is loaded. The physiotherapist can always press on the cancel button which cancels the action: no folder or file is created, no changes are made on the patients list.

As said before, the name and next session date can be changed in the *PatientScene* (see Figure 6.14). This scene for a patient is loaded, if the physiotherapist clicks on the patient in the list. The patient's account can be also deleted by clicking on the delete user button. With this, the patient's folder with all the files in it is deleted and the scene changes back to the *StartScene*. By pressing the statistic button, *StatisticScene* is loaded. Here, the physiotherapist has the option to record a new exercise. Therefore, they can press on the record exercise button and the *RecordScene* is shown.

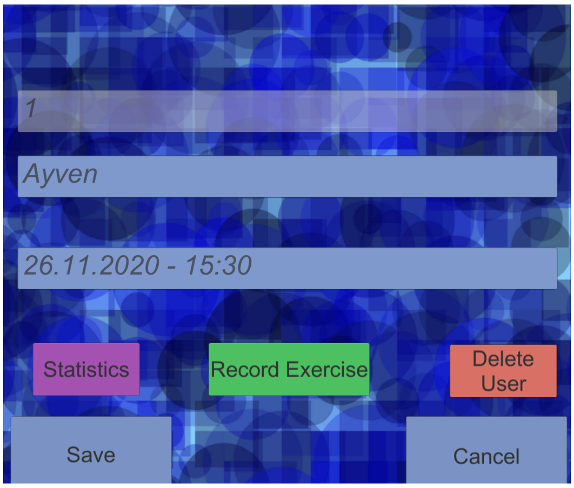
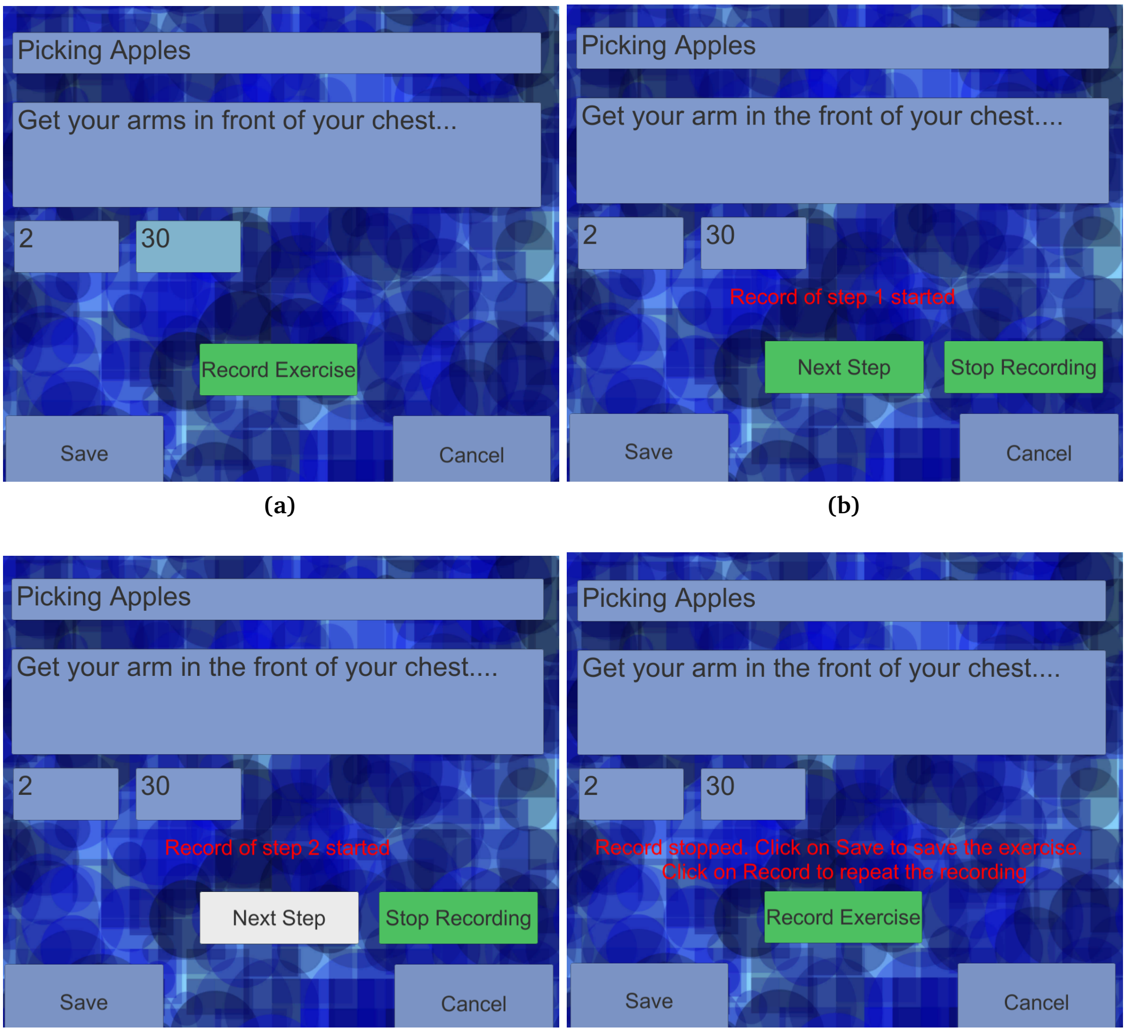

1
Ayven
26.11.2020 - 15:30

Figure 6.14: The patient's scene of the physiotherapist's application. In this scene, the name of the patient and the date of the next session can be changed. Furthermore, new exercises can be recorded, the statistic scene can be called and the patient can be deleted.

In the *RecordScene*, the physiotherapist can input a name and a description for the new exercise, as well as a number for repetitions and sets (see Figure 6.15). For example 20 repetitions in three sets. By pressing on the start record button, the record starts after a countdown of five seconds. In the next subsection, it is explained precisely, how the recording is working. By pressing the save button, in the exercise.txt file in the folder of the patient, the exercise is added, and record files are saved in the folder, as well as a file for the description of the new exercise.



Picking Apples

Get your arms in front of your chest...

2

30

Picking Apples

Get your arm in the front of your chest....

2

30

Record of step 1 started

Picking Apples

Get your arm in the front of your chest....

2

30

Record of step 2 started

Picking Apples

Get your arm in the front of your chest....

2

30

Record stopped. Click on Save to save the exercise.
Click on Record to repeat the recording

(a) (b)

(c) (d)

Figure 6.15: Recording Scene of the physiotherapist's application. a) The physiotherapist can enter a name and a description of the exercise, as well as the number of sets and repetitions. b) Pressing on the record exercise button starts the recording of the first step after a countdown. c) Recording of the second step started by clicking on next step button. d) Stop recording has been pressed. Physiotherapist can decide if they want to rerecord or save the exercise.

The statistic scene is the same as in the main application, but the update-data button does not exist and the physiotherapist can choose between the patients. If the physiotherapist selects a patient, the exercises and plots of this patient will be loaded and shown (see Figure 6.16).

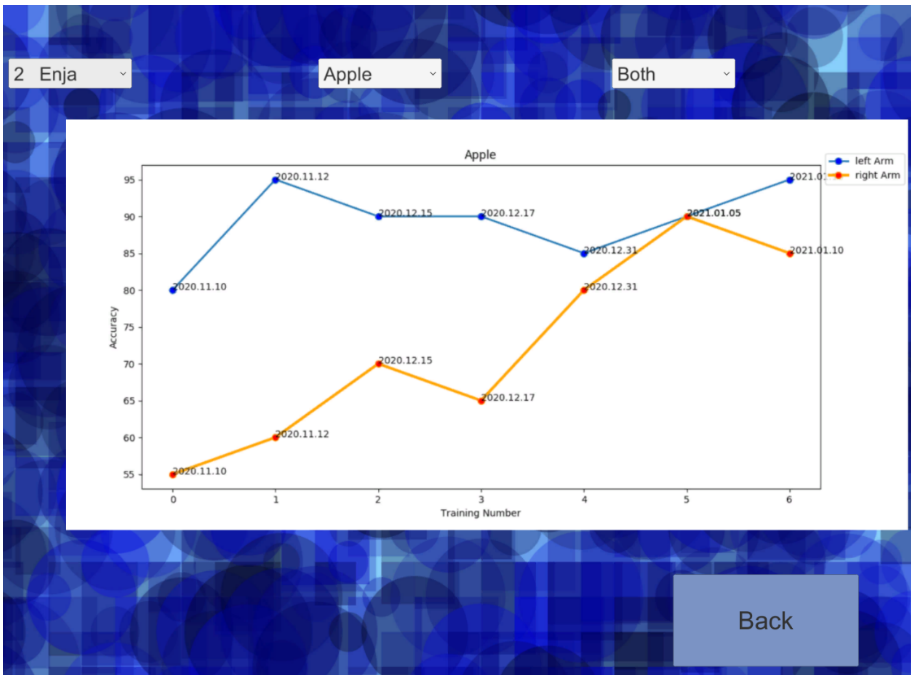


Figure 6.16: Statistic scene of the physiotherapist's application. The physiotherapist can select between the patients, the exercises and the arms.

6.2.2 Motion Tracking

Due to individual anatomy with respect to size and the fact, that people are having different ranges, the exercise movement of the arms should be recorded by the patients themselves. As the interviewed physiotherapist mentioned for example in the picking apples exercise, many people cannot raise their arms straight into the sky without leaning their back back. For those people, it would be better to make the exercise with an angle to the front. So, when they record the exercises under the supervision of the physiotherapist, their limits is already in it.

To record the exercise, the patients must wear the VIVE trackers. One on each shoulder, elbow and wrist. The trackers are connected to empty objects with the asset *VIVE Input Utility* and the component tracked object. The positions and rotations of the empty objects are saved in arrays and by pressing the save button, those arrays are stored in files in the folder of the patient.

Most of the exercises consist of couple of steps. Especially the last two steps (going up and going down, turning left and turning right, etc.) must be repeated to reach the number of repetitions. Therefore, the start button changes to a next step button. By pressing the next step button, a countdown of two seconds starts and "_ " is written into the arrays. The recording ends by pressing the end record button. Now, the physiotherapist can decide, if they want to rerecord (by clicking on the record button again) or save the recordings (by clicking on the save button).

7 Evaluation

To get a better understanding of the system and how the users would like it, an evaluation is mandatory. Normally, a user study would take place with people trying out the system and give feedback on it. Unfortunately, because of the COVID-19 virus, it was impossible for us to conduct a study. Still, we wanted to get an evaluation, that is why we went a unconventional way: we conducted the study online with videos. To get a small comparison to the online questionnaire, we ran a pilot study with one person. In this chapter, the online questionnaire and the pilot study are explained and the results are shown.

7.1 Online Study

In this section, the online study which was taken to get an evaluation on the prototype is described. At first, we talk about the preparations and call for the study, then a short section about the participants and at the end the results.

7.1.1 Preparations

Because of the COVID-19 virus and the lockdown, we could not invite the participants to our lab to try out the system. So, we created videos and a questionnaire, which we uploaded to Google forms and sent firstly, to the participants from the previous interview and secondly, to anybody who was interested.

Five videos have been created for the online study, all with the length of about one minute. The first video was about the hardware we are using. We showed pictures of the HTC VIVE, the VIVE controller and the vibration bands, of course with some explanations about how they are going to be used. The other videos have been recorded with the *Unity recorder*. This recorder is an editor recorder which can be installed in the Package Manager → Advanced → Show preview packages. The second video was about the GUI. In this video, a walk through started with entering an ID and ended with the statistic scene was recorded. The other three videos were about the modalities and the exercises. Because we can not evaluate about the vibration devices with videos, only the other modalities had been taken into account. In the videos, the ghost arm was combined with the Apple exercise, the virtual physiotherapist with the rotating the spine exercise and the auditory guidance with the Wings exercise. In the exercise videos, also the settings for the exercises were shown.

Beside questions to the person (age, gender, profession, their reason to see a physiotherapist and if they have worn VR glasses before), to each video a question section was created in the questionnaire. The sections starts with an explanation about what the participants will see in the video, followed by the video itself and by a System Usability Scale (see Section 5.3). For the hardware section, we renamed „System“ to „Hardware “ in the questions. Because the possibility of having music in the training sessions, we added the music in the physiotherapist video as well as in the ghost arm video. For those two sections the question, if the music was distracting, was added. Then we have asked the participants what they had liked best and worst and what could be improved. After all sections, the participants were ask to put the modalities into an order of which they liked most and which last.

To prevent a bias of the modalities, we shuffled the order of them. To do that in a single questionnaire (unfortunately shuffling sections is impossible in Google forms), after the GUI section, the participants could choose between A, B and C. This decision affected the order of the exercises as in Table 7.1. The three different orders are based on the Latin Square.

	1st Modality	2nd Modality	3rd Modality
A	Ghost arm	Virtual physiotherapist	Auditory guidance
B	Auditory Guidance	Ghost arm	Virtual physiotherapist
C	Virtual physiotherapist	Auditory guidance	Ghost arm

Table 7.1: Orders of the modalities based on the decision of the participants

7.1.2 Participants

To be able to differentiate between the participants from the previous interview and the new participants, we handle them both separately and together (see Table 7.2).

From the participants interviewed for the requirements, five have been willing to take part part in the evaluation, three male and two female. The mean of the ages has been 40.4 (SD = 18.13). Three participants were retired, while one was student and one working in the management. One participant was suffering from Niemann-Pick Type C, one from the consequences of a stroke and one from MS. The other two did have sports injuries back at the interview. Two participants have worn VR glasses before.

22 new participants took part at our online study, 13 male and 9 female. The mean of the ages has been 32.23 (SD = 13.12). The professions of the participants can been seen in Figure 7.1. Not all the participants were seeing a physiotherapist, but for those who did, the reasons have been scoliosis, rheumatism, (sport) injuries, disc prolapse and pain because of tensions in the back and neck. 68.18% of the participants have worn VR glasses before.

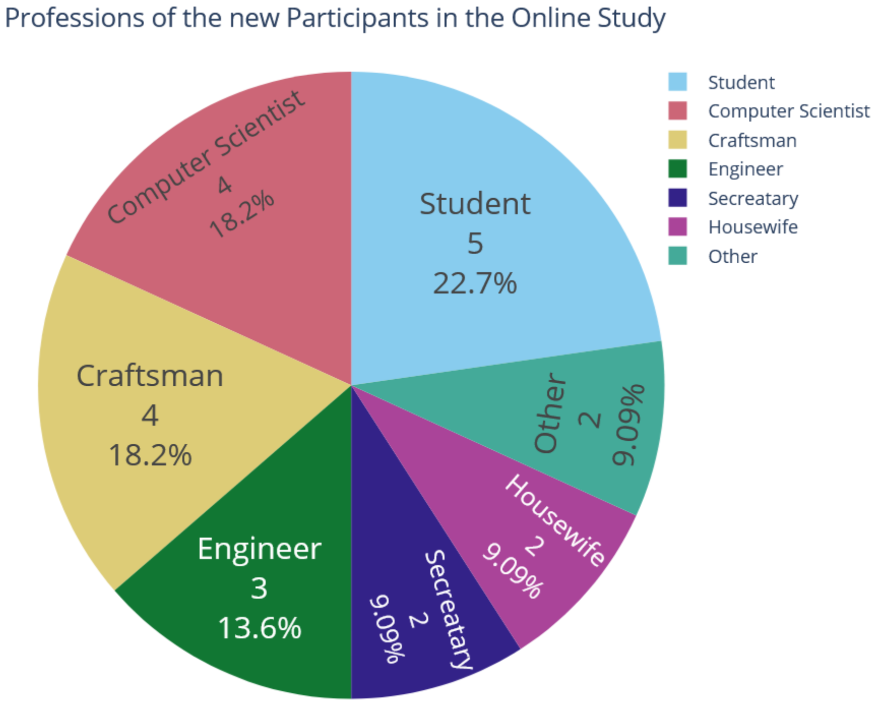


Figure 7.1: Professions of the new participants

	Previous Participants	New Participants	All Participants
Gender (male / female)	3 / 2	13 /9	16 / 11
Age (mean / SD)	40.4 / 18.13	32,23 / 13.12	35.70 / 13.96
Worn VR glasses (%)	40	68.18	62.96

Table 7.2: Data of the person from the participants of the previous interview, the new participants and all together

7.1.3 Results

In this section, we first take a look at each section of the online study separately, with the results of the SUS's and the comments the participants made, and then compare the three modalities. To find a possible difference between the previous and the new participants in the SUS rating, t-tests have been carried out. We used the application JASP[1] for the calculations.

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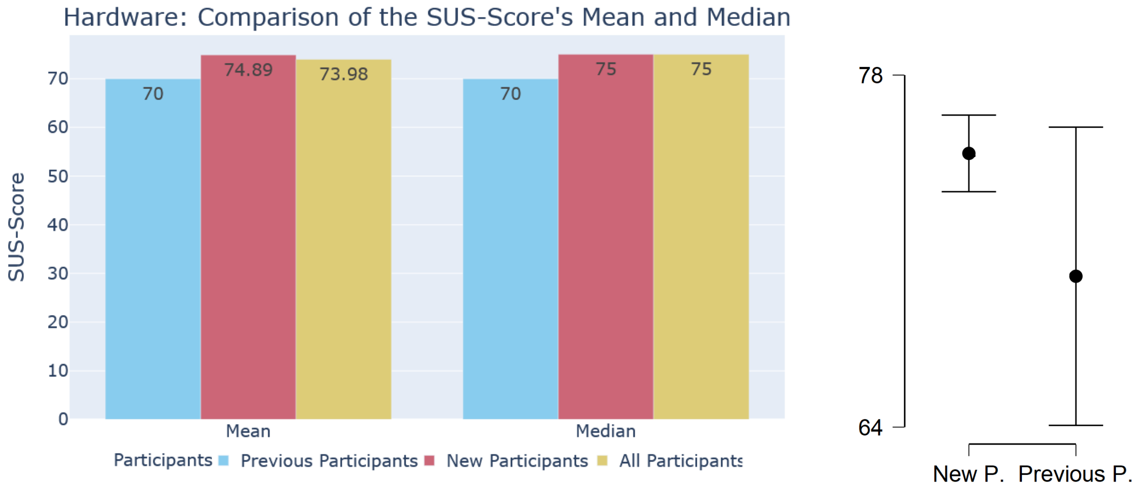
[1] https://jasp-stats.org/

Hardware

The first section has been the hardware. In the hardware video a pictures of the VIVE has been shown, a well a the controllers with the trigger marked. A picture and short video of someone wearing the trackers and the VIVE glasses is shown. At the end of the video the vibration bands are pictured and explained.

The result of the SUS of the previous participants has been in mean and median 70, while for the new participants the SUS result has been 74.89 in mean and 75 in median. Both together having a mean of 73.98 and a median of 75 (see Figure 7.2). We compared the scoring of the previous participants with the new participants with a one-tailed t-test (new participants > previous participants; see Table 7.3). The p-value was 0.02 which leads to a significant difference towards the new participants. But it is here to mention, that due to the low number of previous participants this result is not that significant.



(a) (b)

Figure 7.2: Evaluation on the hardware a) Mean and Median of the hardware b) Confidence interval (0.95%) of the SUS from previous participants and new participants

Measure 1	Measure 2	t	df	p	Mean Diff.	SE Diff.	Cohen's d
New P.	Previous P.	2.979	4	0.020	9.000	3.021	1.332

Table 7.3: Paired Samples T-Test for the hardware. The p-value of 0.02 leads to a significant difference.

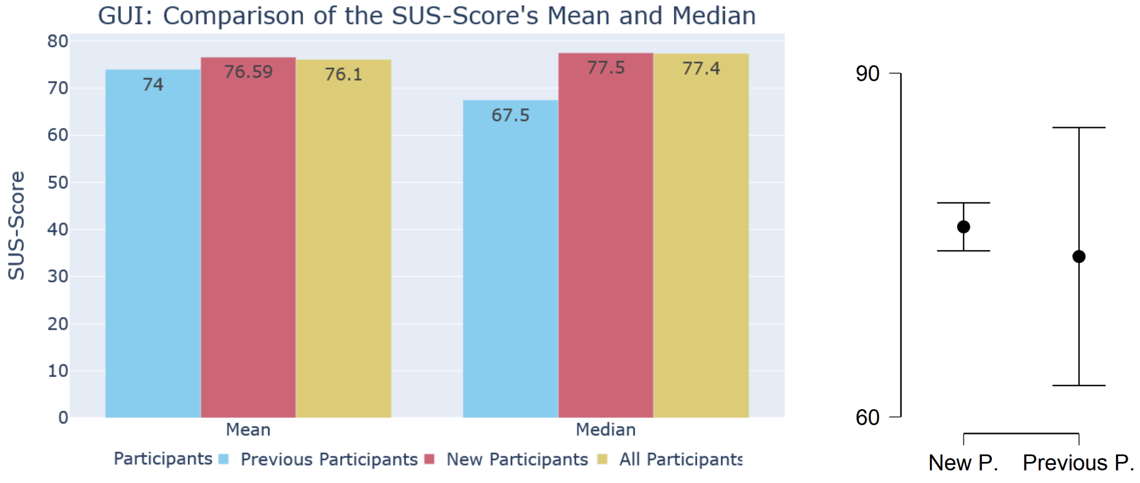
It is very interesting what the participants had to say about the hardware. Some of them liked the idea behind the whole system and mentioned that VR might increase the motivation for training at home, especially in the times of Corona. Other said, that they liked the haptic device a lot and could imagine that this guidance would work well.

A big drawback many of the participants mentioned was the laboriously putting on of the trackers and the vibration devices. Another participant said, that the hardware was quite expensive and asked if it would be rent for the using time. The last big drawback which was mentioned multiple times was that the freedom of movement would be limited with this hardware.

GUI

The next section in the questionnaire was about the GUI of the prototype. In the video for that, every GUI scene except from the settings for the exercises has been shown and clicked through. The video starts with the ID scene, goes over the menu scene to the settings, changes language and name, and stops at the statistic scene.

The previous participants rated the GUI with a mean of 74 and a median of 67.7, while again, the new participants rated it at little higher to a mean of 76.59 and a median of 77.5. In total the mean is 76.11 and the median 77.5 (see Figure 7.3). The result of a one-tailed t-test (new participants > previous participants; see Table 7.4) has a t-value of 1.482 (p-value = 0.106) which leads to the conclusion that there is no significant difference in the participant groups.



(a)

(b)

Figure 7.3: Evaluation on the GUI a) Mean and Median of the GUI b) Confidence interval (0.95%) of the SUS from previous participants and new participants

Measure 1		Measure 2	t	df	p	Mean Diff.	SE Diff.	Cohen's d
New P.	-	Previous P.	1.482	4	0.106	8.500	5.734	0.663

Table 7.4: Paired Samples T-Test for the GUI. The p-value of 0.106 leads to no significant difference between the new and the previous participants.

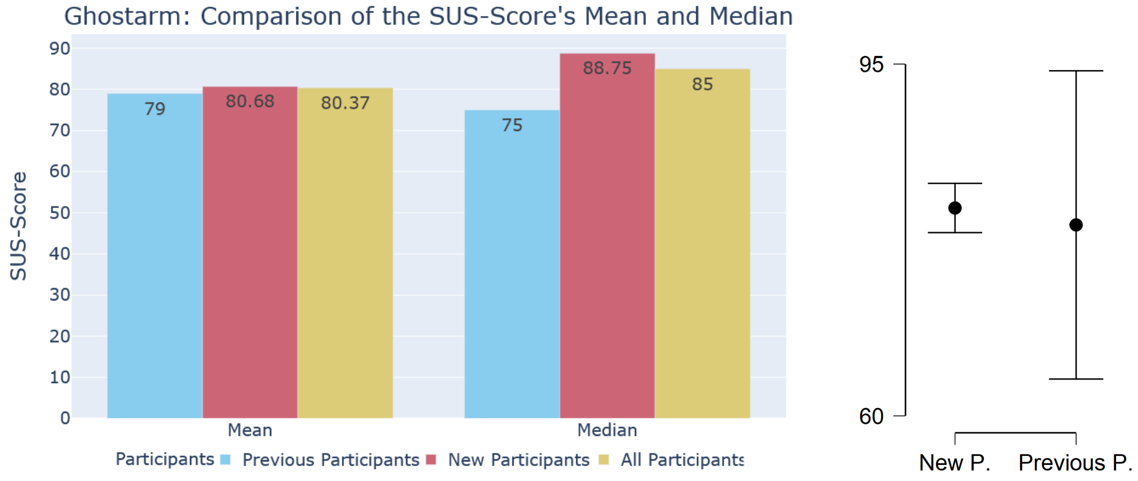
About how the room looks like, the participants are in two minds. The one side likes the room and the secretary in the background, they even seem real. One participant said: „It is kept simple, no unnecessary frills.“ The other side said, that the room could be nicer and is distracting. They wished for a neutral background or a having the menu outside on the grass.

The same goes for the menu it self: one side think is it pretty and easy to use, even self-explanatory, while the other side wanted a nicer design and a change of the sizes of the buttons and the input fields.

Ghost Arm

One of the modalities which were shown was the ghost arm. In the video, first the settings for the exercise have been shown and ghost arm, the exercise apple and music were selected. Then the exercise started and the participants could see the user following the ghost arm.

As in the section GUI, the mean of the previous participants' score (mean = 79) and the new participants' score (mean = 80.68) are pretty similar, but the median differs more (median previous participants = 75, median new participants = 88,75). In total, the mean is 80.37 and the median 85 (see Figure 7.4). A one-tailed t-test (new participants > previous participants; see Table 7.5) showed that medians were not too far away to become different groups. With a t-value of 0.512 (p-value = 0,636), there is no significant difference.



(a) (b)

Figure 7.4: Evaluation on the modality ghostarm a) Mean and Median of the modality ghostarm b) Confidence interval (0.95%) of the SUS from previous participants and new participants

Measure 1		Measure 2	t	df	p	Mean Diff.	SE Diff.	Cohen's d
New P.	-	Previous P.	0.512	4	0.636	4.000	7.810	0.229

Table 7.5: Paired Samples T-Test for the modality ghostarm.The p-value of 0.636 leads to no significant difference between the new and the previous participants.

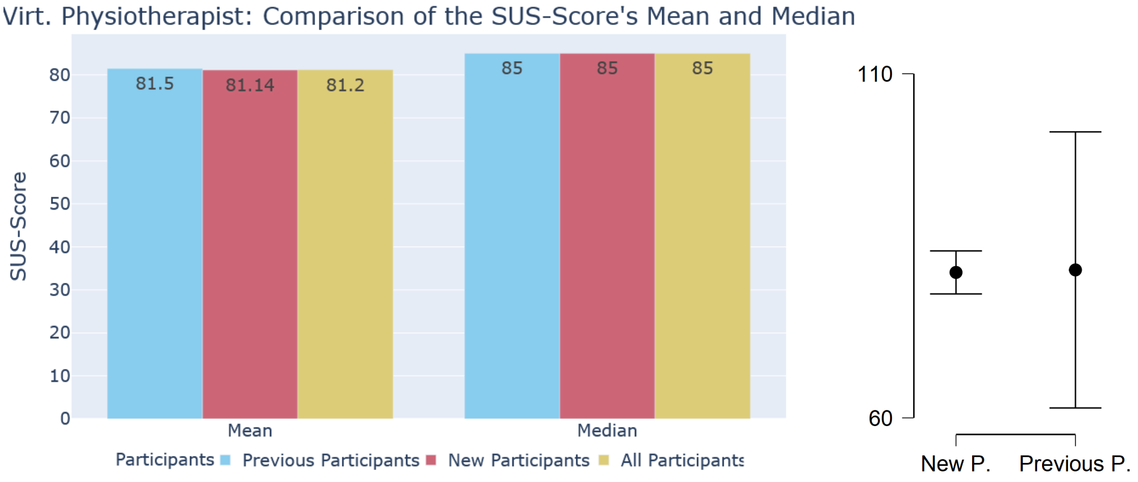
The simplicity of doing the exercises with the ghost arm was the most mentioned like. The participants said, with the ghost arm, is it possible to see exactly what to do and where to put the arm. It was easy to differentiate between the arms, but one participant mentioned that ghost arm should be half-transparent. Others wanted the ghost arm to be more arm-alike, not only “sticks with balls“.

The background music was a relevant point to some of them. Many of them said, that the music was good and wanted, but they wanted to choose their own music. One of them commented, that the music distracted them, what leads us to the last question which was asked in the questionnaire in this section: “The music distracts me from the exercise “. The question was in the style of the Likert scale as the SUS questions before and got a mean of 2.93 (after inverse the numbers). 14 participants strongly disagreed on the statement and two strongly agreed.

Virtual Physiotherapist

The video of the physiotherapist was basically the same as the ghost arm video before, but with different settings in the *training_scene* and of course, the exercise was shown with the physiotherapist. Unfortunately, it happened, that on the video the physiotherapist seemed to be further away than with the VR glasses.

The means of the participant groups are very similar again, even almost the same: previous_mean = 81,5 (median = 85) and new_mean = 81,14 (median = 85). In total, the mean is 81,20 and the median = 85 (see Figure 7.5). Because of this similarity, we decided to forego the t-test.



(a) (b)

Figure 7.5: Evaluation on the modality virtual physiotherapist a) Mean and Median of the modality virtual physiotherapist b) Confidence interval (0.95%) of the SUS from previous participants and new participants

As with the ghost arm, the participants perceive the virtual physiotherapist as understandable and easy to follow. They also liked, that the situation felt similar to with a real physiotherapist. Furthermore, one mentioned, that also complex exercises would be able to show with the virtual physiotherapist.

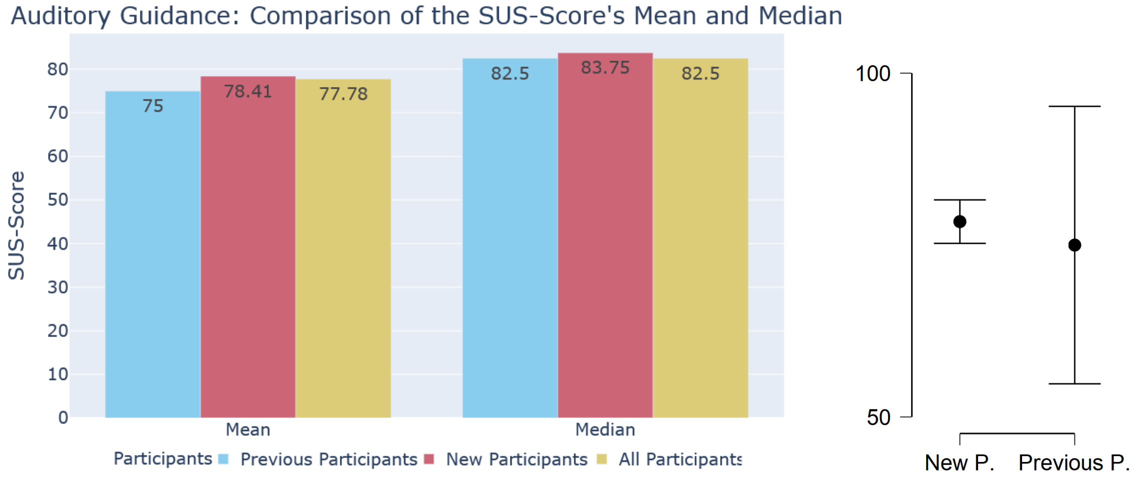
On the other side, as said before, the physiotherapist seemed to be too far away. This also let a participant not being sure if the physiotherapist is actually standing or kneeing down (the virtual physiotherapist is sitting), and another was asking, if the therapist has forearms, because they could not see them.

Despite from the issue of the physiotherapist being too far away, the music was a topic again. As in the ghost arm section, some of them liked the music, some wanted something more relaxing or be able to choose their own music. In this section, we also asked if, the music was distracting, with a mean score of 2.59. This is a little lower than with the ghost arm.

Auditory Guidance

The last modality is the auditory guidance. In the video, the settings for the exercise differs again to the previous modalities and the music is turned off. In the exercise, no ghost arm or physiotherapist is to see, but the exercise is explained as recorded voices.

The mean of the previous participants is 75 and the median 82.5, while of the new participants, the mean is 78.41 and the median 83.75. For all participants the mean is 77.78 and median 82.5 (see Figure 7.6). The one-tailed t-test (new participants > previous participants; see Table 7.6) showed no significant difference with a t-value of 0.243 (p-value = 0.41).



(a) (b)

Figure 7.6: Evaluation on the modality auditory guidance a) Mean and Median of the modality auditory guidance b) Confidence interval (0.95%) of the SUS from previous participants and new participants

Measure 1	Measure 2	t	df	p	Mean Diff.	SE Diff.	Cohen's d
New P.	Previous P.	0.243	4	0.410	2.500	10.277	0.109

Table 7.6: Paired Samples T-Test for the modality auditory guidance. The p-value of 0.41 leads to no significant difference between the new and the previous participants.

The most named positive aspect from this guidance was the auditory guidance itself and that they liked the voice, but the participants were missing more information. They did not know, how low they must put their arms, and also were not sure if they would do the exercise correctly. So, they wished for a combination of the voice with something visual, either ghost arm or physiotherapist or even, one participant said, the user's arm itself could give feedback with for example the coloring. Furthermore, they did not notice the canvas with the repetitions and sets, because they wanted the voice to tell how many repetitions were left.

Comparison

One thing which came out clear from the online study was, that the participants wanted to be able to use more than one modality - most a combination of either the ghost arm or the virtual physiotherapist together with the auditory guidance. Fortunately, this is already possible with the prototype. Still, at the very last question, we asked them to rank the modalities from best to worst (see Figure 7.7). Most of them ranked the auditory guidance worst. The ghostarm was ranked best at most, but also a lot of participants perceive the ghostarm as worst. The virtual physiotherapist seems to be liked best, since, but in one case, it is ranked either best or middle. We also asked the participants to explain their decision for the ranking. Some reasons to pick the gostarm as best were (translated from German):

- “One sees best at the ghost arm what mistakes one is doing and how to do it correctly.“
- “Ghost arm is the clearest and most accurate guidance with visible accordance.“
- “With the ghostarm I can check best, if I am doing it correctly.“
- “To be honest, I though everything was easy to understand, but the ghost arm seemed to be unbelievably understandable.“
- “Ghost arm is the most accurate (modality) and intuitive. With the virtual physiotherapist, some movements might be hard to recognize. Furthermore, the physiotherapist has the „your right side or mine?“ - problem. “

Other liked the physiotherapist more with following reasons:

- “Audio and a virtual trainer are the closest to a real training.“
- “The physiotherapist is more comfortable and one can take a close look on how it is done.“
- “Virtual therapist is the easiest one to follow.“
- “The virtual therapist take the whole body into account.“

For the auditory guidance, the reasons had been:

- “The spoken guidance was more clear.“
- “The auditory guidance was the easiest guidance. “

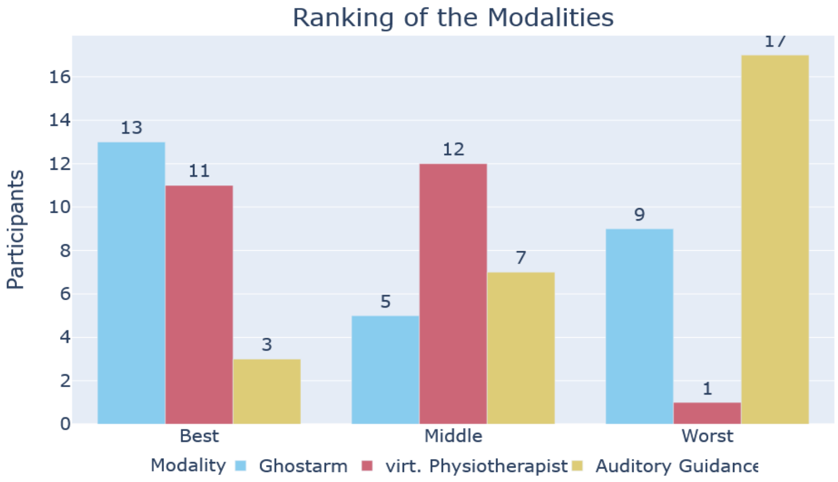


Figure 7.7: Ranking of the modalities by the online participants

For us, it is also interesting, if the SUS scorings for the three modalities differ significantly. For that, we first created a box plot (see Figure 7.8) and then used a MANOVA (multivariate analysis of variance; see Table 7.7) for a quantitative result. Already in the box plot, it seems that there is no significant difference, what the MANOVA also showed by a F-value of 0.22 (p-value = 0.8).

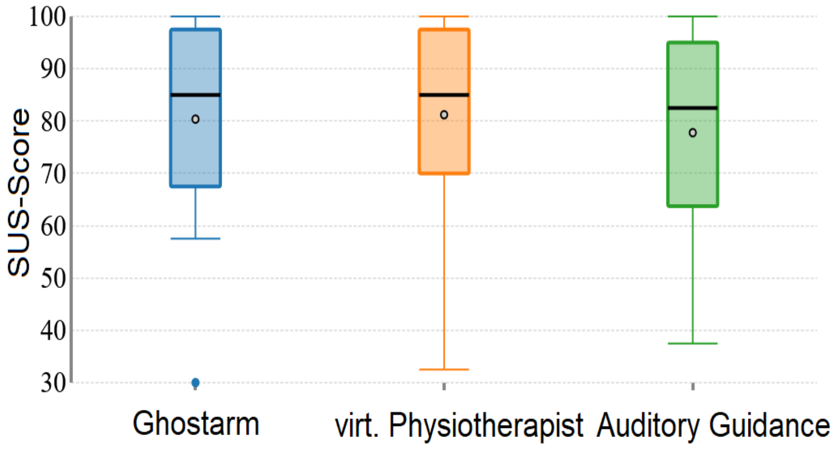


Figure 7.8: Box plots of the modalities

Cases	Sum of Squares	df	Mean Square	F	p
Modality	172.377	2	86.188	0.220	0.803
Residuals	30530.093	78	391.411		

Table 7.7: MANOVA - Comparison of the three modalities' SUS score. The p-value of 0.803 leads to no significant difference between the three modalities.

7.2 Pilot-Study

By only watching videos of a person using the system, the system can not be fully rated. Therefore, a feedback of someone who is trying out the system for the first time is mandatory. For this, a supervisor of this thesis volunteered to participate at a pilot study.

7.2.1 The Study

Like the online study, this study also consisted out of sections and SUS questionnaires. Instead of watching a video, the user tried out the system. The questionnaire also started with the data to the person, then a section about the GUI, followed by the ghost arm section, the virtual physiotherapist, the auditory guidance and finally, the haptic guidance.

After the participant answered the questions to the data of the person and it was explained what the study is about, the VIVE trackers were put on. Because of the hygiene, we could not help to put on the trackers and the participant needed to do this on their own. Then, the trackers and the controller were turned on, which led to the first two issues: even if they have been charged before, one of the trackers did not turned on. So, we decided to run the study with only the right arm. The second issue which occurred right at the beginning was, if the controller was turned on, the last tracker was recognized by Steam VR, but did not move in Unity. To get a fast solution for this problem, we decided to use the trackers and controller separately and first started with the guidances and the GUI afterwards.

The first guidance we selected was the ghost arm with the exercise Apple. Even tough the difficulty was accidentally set to hard, the participant was able to trigger the next steps. They mentioned, that the shoulder balls are not visible with the VR glasses, what makes it difficult if the shoulder of the user's arm must be close enough to the shoulder of the ghost arm to set the trigger for the next step. Because, we could also see the same the participant could see, we were able to set the trigger with the keyboard, which helped the participant a little when they a struggling with the trigger. Furthermore, the ghost arm was a recorded by us and the arm length did not fit with the user's arm.

The second guidance was the auditory guidance with the exercise Wings. The only thing here to mention is, that the participant did not got the exercise correctly by just the voice and was doing something completely different.

Then the virtual physiotherapist and the exercise Spine were tested. The participant was able to follow the exercise correctly, but again needed help with triggering the next step. Because this exercise is more about the upper body than the arms, the participant said, that it would be nice, to have an virtual avatar to be able so see themselves, either on the chair they are sitting, or in a mirror.

The last guidance was the haptic feedback. Unfortunately, technical WiFi issues came up, which forced us to use a notebook on which the system was also running, but the VIVE glasses and trackers could not be connected to. Again, we used the exercise Apple to let the participant try out the haptic device. Even the signals had been sent correctly, for the participant it felt like the whole band is vibrating and they could not distinguish between the single motors and therefore, could not follow any guidance.

At the end, we also showed the GUI which was controlled with the VIVE controller. Everything but the dropdowns worked very well. It took the participants a few tries to get the things selected they wanted in the dropdowns.

After each trial, the participant was filling out the SUS questionnaire. At the end the participant were ranking the guidances as in the online study.

7.2.2 Results

The participant who was one of the thesis' supervisors was 26 years old, female and a researcher. She did wear VR glasses before.

The first section on which a closer look is taken, is the GUI. As said in the previous section, the participant had problems to hit the dropdown menus accurately, which also led to the rating of the GUI to a SUS-score of 47.5. This score is within the second standard deviation of the participants from the online study (SD = 16.35). The participant liked the secretary in the office room, but disliked the clicking function of the trigger in the dropdown.

The ghost arm was the first modality in the study. Here, the SUS-score is 70. The score is within the first standard deviation of the online participants (SD = 19.57). The participant liked that she was able to complete the movements. She disliked the position of the arm, because she could not see her shoulder and therefore, didn't know, if the shoulder was on the right position. She also mentioned, that it would be better, if the ghost arm was half-transparent.

The next guidance was the auditory guidance. With this guidance, the participant was not able to do the exercise correctly, which is reflected by the SUS-score: 27.5. Compared to the SUS-score of the other participants, this score is in the third standard deviation (SD = 20,29). As the online participants, she liked the idea behind the auditory guidance, but not knowing, if you are not close enough to the invisible ghost arm to trigger the next step, or if you are doing the exercise completely wrong, was her drawback of the auditory guidance.

The SUS-score of the virtual physiotherapist was 32.5 which is also in the third standard deviation from the online participants (SD = 19.48). The problem the participant had with the virtual physiotherapist was that she could not compare herself to the therapist and did not get any feedback on her movements. *„It would be great to see my body in a mirror.“*

The last guidance in the pilot study was the haptic guidance. As in the previous section described, the participant could not distinguish between the motors and did not know where to move the arm. That is the reason why the SUS-score for this is only 15.

The ranking of the guidances is that the participant liked the ghostarm most, followed by the physiotherapist. With those two guidances, she was able to do the exercises correctly. Because she did the first step of the exercise with the auditory guidance correct, the auditory guidance on the third place and last is the haptic guidance.

8 Discussion and Limitations

In this chapter, we discuss the prototype and its evaluation. First, we take a look on the hardware, then the GUI and the modalities.

8.1 Hardware

The hardware of this prototype consists out of the HTC VIVE, six VIVE trackers, the VIVE controller and the vibration devices. Last is handled separately with the modalities. The VR glasses are connected to the computer with a long cable (almost 5 meters). Cables always come with the danger of falling over them while walking, jumping or turning around. Even tough our prototype only includes sitting exercises, in the future, more exercises might be added, which are not only sitting, for example star jump. This issue can be easily solved with the wireless adapter for the VR glasses.

A bigger issue for our prototype are the trackers. Six trackers must be put on, and for using the system at home, sometimes put on by oneself. While implementing and trying out the system, it already took long and was frustrating to put on the trackers without any help - especially with the other handed arm. Also, in the evaluation, some online participants said, that dressing on the trackers might be more exhausting than the actual training. The participant of the pilot study took a long time (>5 minutes) to put on the trackers and got frustrated as well. This prototype is specially for people with motion disabilities. They would have even more problems with putting on the trackers. Therefore, an easier tracking system should be used.

8.2 GUI

The GUI consists out of multiple scenes as described in Section 6.1.1. Each of those scenes includes two canvases, one for the mouse and one for the VIVE controller. Since the mouse cursor is small and users are used to it, it is easy to control the GUI. With the VIVE controller is it different. The canvas from the *VIVE Input Utilities* from the Unity asset store provides examples for everything for the control with the controller: button, slider, toggle, dropdown, input field, etc. Even a virtual keyboard is provided for the input field. Unfortunately, this got lost after a forced Unity update at the very end of the implementation and in the week of the pilot study. Because of that, the user can click on the input field with the VIVE controller, but needs a keyboard for the actual input.

Also, and what is worse than the input field, after this update the dropdown menus became an issue. Before, the dropdown opened and the user could select something. Now, the dropdown still opens, but it takes multiple clicks to be able to make the selection accepted. This leads to an inconsistent system and is not user friendly.

Some participants from the interview mentioned, that they liked the rooms and the GUI is easy to understand and nice. Despite from the issue with the controller, the GUI seems to be liked. The canvas are not overloaded and it is self-explanatory what button leads to what scene. The *statistic_scene* has been brought up by two previous participants in the online study. In the interview, they required a statistic in which they can see progress to get more motivated. Even though the graph in the *statistic_scene* is only temporally, the participants seemed to like it and it was important to them.

8.3 Modalities

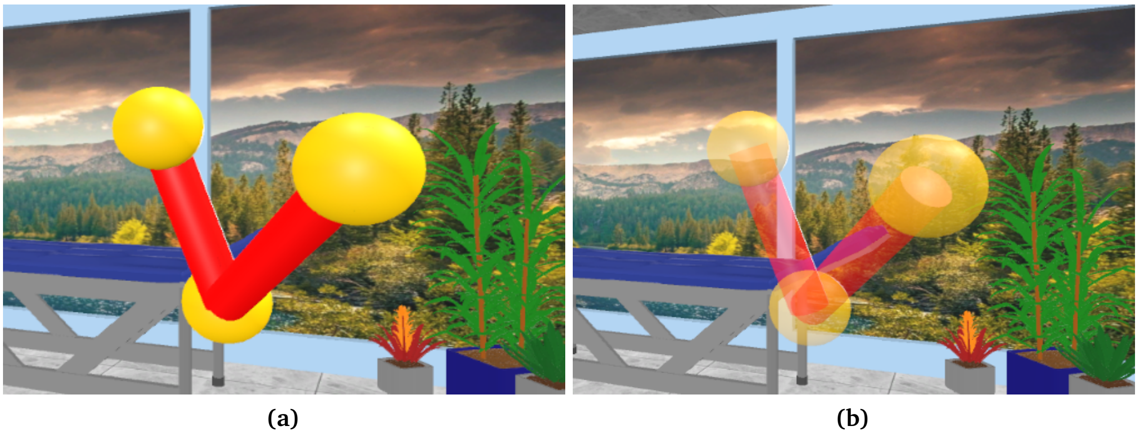
Each of the four modalities is discussed in this section. The feedback from the evaluation is taken into account. First, we start to discuss the ghostarm, followed by the virtual physiotherapist and the auditory guidance. At the end, we talk about the haptic guidance.

8.3.1 Ghostarm

Both the user's arms and the ghost arms consists of six spheres (three each arm, one for shoulder, elbow and wrist) and cylinders as the parts in between. The user's arms are colored in green-blue, while the ghost arms are orange-red. With the ghost arm the user can directly see, where the goal positions are and try to match their arms with the ghost arm.

In the pilot study, the participant mentioned, as well as one participant of the online study, that it would be better and more understandable, if the ghost arm was half-transparent. Because we were also thinking about this already before the study, we changed this directly after study (see Figure 8.1).

Furthermore, in the pilot study the participant said, that due to the VR glasses, she could not see the shoulder. Not seeing the shoulder causes the problem, that for triggering the next step, all joints must match within the threshold. There is no option to move the arm manually further away from the camera to be able to see the shoulder, because this is representing the real shoulder. Even if we shifted both arms for example ten centimeters, this might cause an uncanny effect. The only solution is to take out the shoulders from the triggering function and just want the elbows and wrists to match.



(a) (b)

Figure 8.1: Ghostarm a) non-transparent b) half-transparent

8.3.2 Virtual Physiotherapist

The virtual physiotherapist was a requirement from almost all participants of the interview. From an online 3D human and animation side, we downloaded a human model and created the animations for the exercises with Autodesk Maya. These animations are played with the virtual model, if the user selects the therapist as a guidance.

The online participants seemed to like this guidance, what their ranking at the end of the questionnaire showed. They said this gets closest to a real physiotherapist, but one mentioned, that this guidance does not differ from a video. This statement we agree on partially. The difference from a video to this guidance is, that the physiotherapist waits for the next step until the user has ended correctly the current step. In a video the user must press pause and play, if the steps are shown too fast and they can't follow. Furthermore, a video does not verify, if the user is doing the exercise correctly.

An advantage the therapist has over the ghostarm is, that the user is able to see the pose of the full body and not only the arm. A suggestion which must be verified in a further user study is, that the with the ghostarm, the user focuses more one the exact position of their arm than the exercise itself. For example, in the Apple exercise, the important part is the activation of the muscles to move the arm up and down, and also to stretch the upper body side. Trying to just fit within the ghostarm, could barely miss the reason for the exercise. With the physiotherapist they might want to copy the movements of the whole body and not only the arms. Therefore, maybe the thresholds of the trigger should be adjusted again.

8.3.3 Auditory Guidance

For the auditory guidance voice commands for every exercise for every step has been recorded, as well as a praise to keep up the motivation. Those recordings has been included into the system and are played when the auditory guidance was selected.

In the online study, the feedback on the auditory guidance was positive, even though it was ranked last. In the pilot study, the auditory guidance was not successful. The participant did not know what to do and did complete wrong movements. The reason for this might be, that the participant did not know the exercise before. In the real scenario, the users were showed and explained the exercise previous in the physiotherapy session and they also would have done the exercise before for the recording. A suggestion here is, that the auditory guidance would work better, if the user knows the exercise in advance.

In both the auditory guidance and the physiotherapist guidance, the user does not get any feedback to the movement but the next step when they reached the goal position. To not get any feedback within the steps might frustrate the users and might lower the motivation a lot. For example, in the Wings exercise, the command “Lower your arms“ is clear, if the user knows the exercise. But when the user is not triggering the next step, they do not know, if they not low enough yet, or if they are even too low already. One possibility is to change the color of the user’s arms, when they getting closer. Since the joints of the ghostarm are red, the user’s arm joint could turn from blue into red, the closer the joint gets to the goal position, and turn back, if the user already passed the goal position. This would work for both, the auditory system and the virtual physiotherapist. Another idea is to prepare more voice commands, to interact with the user within a step (e. g. „Lower“→„Lower“→„Lower“→„Higher“, if the user is already too low). But this would probably become very annoying for the user after a while.

8.3.4 Haptic Guidance

The vibration bands were built by out colleagues from Munich, as well as they prepared the Arduino script for us. There are four bands, one for each upper arm and one for each forearm. Every band includes four motors which can be activated separately with a strength between 0 and 255. The vibration bands are connected to the system over a WiFi socket connection and the system sent JSON files to the vibration band to set values of the motors.

Unfortunately, it was not possible to show the function of the haptic devices to the online participants, but we have shown a picture and explained, what the bands are doing. Some participants liked the idea of the haptic guidance. One participant said, it was like the physiotherapist would lead the patient towards a direction by pushing.

In the pilot study, we could let the participant try it out. The vibration of one motor was transmitted over the whole band, so that she could not say, from which motor(s) the vibration was coming from and therefore, did not know where to move the arm to. Since, the correct motors were vibrating and not just all of them (it is possible to feel, if a motor is vibrating, when the one finger is put above and one below the motor), the problem here must be the elastic band which is transmitting the vibration all around. To solve this problem, a way must be found to be able to distinguish between the motors. An idea for that is using four individual bands for one band, each referring to one direction. Here the drawback, that the users need to learn which band is for which direction, before they can actually use it. Another idea is using heat and cold instead of vibration. Chernyshov et al. [CRCK18] built a heat-and-cold band for VR. In their paper, they build a VR game, in which the user needed to throw either fire or ice ball through some goals. When the hand was inside the fire ball, the band got hot, vice versa with the ice ball. As know from the Easter egg search back in our childhood, the parents used to say „Hot“ or „Cold “ to give a hint on the direction. We could use the same principle and the prototype from Chernyshov et al.

9 Conclusion and Future Work

9.1 Conclusion

In this master thesis, a prototype for multimodal motion guidance in VR for people with motion disabilities has been developed. The system was developed for the HTC VIVE and VIVE trackers. The first two modalities have been decided for already at the very beginning: the ghost arm, inspired by Yu et al. [YAM+20] and a haptic guidance, since haptic is a promising way to guide motions [ASFH+17] [SFO+12] [NDGP14].

Because this system would be made to support physiotherapists and their patients, it is important to get their requirements for such a system. For their prototype, Tang et al. [TAT+14] interviewed physiotherapists for requirements, but we also wanted to ask the patients themselves, what is important for such a system. For this, we conducted a interview via an online meeting portal. Seven participants and one physiotherapist took part in our interview. Four participants the were seeing a therapists because of injuries, while the others were suffering from illnesses (stroke, MS and Niemann Pick Typ C). The most important for them was, that the system checks, if the user is doing the exercise correctly, as well as some statistics about how their performance improved. A nice system, in which they would feel comfortable, was required as well. All agreed on that the system should look like a physiotherapist's office or a gym. Music was a big topic of the physiotherapist, when it went to motivation. The users of the system should be able to listen to music while doing the exercises. The participants suggestions about how to guide the exercises have been a virtual physiotherapist showing and explaining the exercises. This led us to our two other modalities: the virtual physiotherapist and the auditory guidance.

We tried to include as many requirements as possible into the system to satisfy the wishes of the participant. We used Unity 2019.2.12f (later 2019.2.20f) as developing engine and Autodesk Maya 2020 for some modelling and the animations for the virtual physiotherapist.

At first, we needed to agree on the exercises and decided for three exercises, which we called "Apple", "Wings" and "Spine". For each step of each exercise, the animations for the virtual physiotherapist which is a 3D human model we downloaded, has been made.

A small program for the physiotherapist has been implemented. With this program, the physiotherapist is able to add, edit and delete patients, and set up the exercises for the patients, including recording the exercise for the individual ghost arm. Also, the physiotherapist is able to see the statistics of the individual users in his program to see their progress.

A part of the main program is the GUI, which consists out of multiple scene to make it able for the user to interact with the system, make settings for the exercises. To be able to get access to the folder, the physiotherapist created, the user must input a unique ID number. Afterwards, they have the chance to change the language or their name, see their exercise statistics or to start the training. To do that, they must select, which exercise they want to do and the guidance(s) they want to train with. Also, they can choose, if they want to train with music, and set the difficulty for the exercise. The difficulty effects the threshold with which an exercise step is considered as valid.

Four modalities have been implemented: the ghostarm, the virtual physiotherapist, the auditory and the haptic guidance. The ghostarms as well as the user's arms consist out of spheres for the joints and cylinders for the upper arm and forearm. The be able to show the exercise with the ghostarms, the with the physiotherapist's program recorded positions of the exercise are read and put onto the joints. The recorded files are recorded step by step, so the reading can be also done step by step. It is important to take into account, that the rare positions of the recordings must not directly put on the joints for the ghost arm, since the users would be on another position in the VR world when recording as they would be at home. For this, the ghost arm must be shifted towards the user's arm at the beginning.

For the physiotherapist, we used a simple 3D human model and animated the exercises with is. This model is sitting on a chair placed in front of the user in the training room. If the physiotherapist was selected, the model showed the exercises step by step to the user. For the auditory guidance, voice commands for every step of the exercises has been made, as well as a praise and a rest talk. Our colleagues from Munich developed a prototype for the haptic devices, vibration bands. Each band consists out of four motors, each able to vibrate in a range from 0 (no vibration) to 255. In a previous study, it was shown, that the users do not feel the vibration below a strength of 140. The be able to set the correct motors active, the intersection of the vector from the ghostarm to the user's arm with the user's arm is computed. Then the motors, on which the intersection is one, gets activated. If the intersection is between two motors, both of them gets activated with a strength related to the distance they have to the intersection.

To be able to trigger the next step, the distances of the ghostarms' joints to the user's arms' joints is calculated and if the distance of all joints is smaller than the threshold set in the GUI, the next exercise step will be shown. The accuracy of the user is calculated by the mean of the smallest distances of the complete path of one step from the ghostarms to the user's arm. Then the mean of the steps and the joints is taken to get an accuracy for each arm.

An evaluation of the system was done by a online study with the participants from the previous interview and new participants. In the online study, the participants were shown videos about the hardware, the GUI, the ghostarm, the virtual physiotherapist and the auditory guidance. After each video a SUS was used to get feedback to the sections. At the end the participants were asked to rank the modalities from liked best to like last. Most of them liked the ghostarm most and the auditory guidance last, but taking into account, that the ghostarm was also ranked often as liked last, and the virtual physiotherapist was either first or second place in the ranking, the physiotherapist seemed to be the best guidance. All SUS (but one) did not show a significant difference between the previous and the new participants. Also, an MANOVA was used to find a significant difference between the modalities, which was negative.

At the end, we also conducted a pilot study with one participant to get feedback of one user who was not watching just videos but trying out the system. Despite from some technical issue while the study, the participant was able to try out every guidance. After each modality, we also asked to fill out a SUS questionnaire. For the GUI the score was way lower than from the online participants, because the user had problems to handle the controller. The SUS-score of the ghost arm was similar to the one by the online participants, but the pilot study participant mentioned, that she could not see her shoulder and therefore, had problems to trigger the next step. With the physiotherapist, the user was able to complete the exercise. but she did not like it, because she did not get any feedback on how she was doing but the next step. The user did not understand the exercise with the auditory guidance and did it completely wrong. Because of the elastic band of the vibration band was transmitting the vibration form one motor all over the band, the participant was not able to tell, which motor was activated and therefore, not able to tell in which direction she should move the arms.

The pilot study brought up some elementary problems the system has and which need to be handled before a real study can follow. Amongst other thing, these changes are explained in the following section, as well as a description for a real user study.

9.2 Future Work

Because this is the first prototype of this project, there still is a lot to do to make it usable for people with motion disabilities. This section explains the changes, which are mandatory to run a user study, as well as a description of the user study itself and further future work on this project.

Before we can conduct a real user study, the feedback from the evaluation, especially from the pilot study, must be taken into account. The first thing, which we need to change is the tracking system. It is arduous to put on the trackers by oneself, in particular if the user has a motion disability. Furthermore, a participant from the online study, who was going to the physiotherapist for over 30 years, said, that not only the position of the arms, more the complete pose is important. For that, we should go with an full body tracking system, using for example the Microsoft Kinect, or the OptiTrack system. With those, the animation of the virtual physiotherapist could be recorded the same time, the patient is recording the exercise for the ghostarm.

The problem with the VIVE controller, which occurred with the Unity update, must get solved. There are two ways, how to solve that. The first one is, downgrading the project's Unity version back to 2019.2.12f, with the hope, that the issues are going to be fixed by that. The second idea is to delete and reimport the *VIVE Input Utility* asset and build all

VIVE canvases new. Even though this will take a while, we are confident, that this will solve the problem.

One outcome out of the evaluation was, that the canvas which tells the number of sets and the repetitions in the exercises scene was overseen by both some online participants and the pilot study participant. This might have been coursed by the font size or by the font color. Because of the variance of the background color, it is difficult to find a good visible color, because the canvas is moving with the camera. Therefore, we suggest a fixed canvas at the opposite wall, make the font size big and use a clearly visible color for the text.

The next thing, which must be changed before we can conduct a user study, is a direct feedback on the movements. For both modalities the virtual physiotherapist and the auditory system, if the next step is not triggered, the user will not know, if they are close to trigger it, if they might have already passed the point, or if they doing the exercise completely wrong. There are many possibilities here, like for example include a mirror in which the users can see themselves, or adding more voice commands, e. g. "More to the right ". Because the users are already having a virtual arm, on which they can focus on, our suggestion would be to give the feedback over this arm. The idea of changing the colors of the arm's joints towards the color of the ghostarm's joints seems to be understood intuitively by the user. This must be of course tested in the user study. Right now, the joint color of the user's arm is blue, while the of the ghostarm's joints is red. Because everyone associates the color red with something bad (traffic lights), the colors of the arms should be switched. So, while the joint is still far away from the goal position, it should be red and turning more into blue (not green, because of people with a red-green visual impairment) as closer the arm is getting to the goal position.

At last, the haptic devices must be improved. A solution must be found for the band not transmitting the vibration all over it. If there is no band which does not transmit the vibrations, we could use four bands with one motor, instead of one band with four motors. For the solution, the user would need to learn which band is for what direction. It must be also evaluated in the study, if the user can is able to distinguish between the bands by just their position of the arm. A vibration pattern could be introduced here, to help the user tell between the bands. For example the band for the front side vibrates once, then pause the again, the band for the back side vibrates twice, etc. Of course, this must be learnt by the user as well, but it will make sure that a differentiation is possible.

Another idea on the haptic device is, that we could use single haptic motors which are stuck directly on the skin. The advantage is that, the vibration would be not transmitted and the user directly feels the vibrating spot. Unfortunately, there are two drawbacks. First, the users must stick the motors on their arms every time by themselves, and second, always on the same position. The second point might be even the worse problem. The last idea to the haptic devices is, that we could use temperature instead of vibration. The motors in which direction one needs to move are getting cold and the closer the user gets to the goal position, the warmer the motors become.

As soon as the mentioned things were adjusted, a user study, which description will follow up, can be made.

9.2.1 User Study

Due to the COVID-19 virus, we were not able to run a real user study. Although, a user study should be conducted as soon as it is possible. To get further results and feedback on the modalities, this study should be about to find the best modality for a physiotherapy system. The independent variables are the modalities: ghostarm, virtual physiotherapist, auditory guidance and haptic guidance, while the dependent variables are the accuracy the participants are having using the modalities, the scores of a SUS-scale for each modality and a NASA TLX [HS88].

To prevent any bias or carry-over-effect, the order of the modalities shown to the participants should be given by the Latin Square in William's design [Wil49] (see Table 9.1).

User ID	1st Modality	2nd Modality	3rd Modality	4th Modality
ID = 0 mod 4	Ghostarm	virt. Therapist	Haptic Guid.	Auditory Guid.
ID = 1 mod 4	virt. Therapist	Auditory Guid.	Ghostarm	Haptic Guid.
ID = 2 mod 4	Auditory Guid.	Haptic Guid.	virt. Therapist	Ghostarm
ID = 3 mod 4	Haptic Guid.	Ghostarm	Auditory Guid.	virt. Therapist

Table 9.1: Modality order for the user study with the Latin Square (William's Design)

For the study, a computer with the prototype running on it, a HTC VIVE, the tracking system, the haptic devices, a consent form, and the SUS and NASA TLX questionnaires should be prepared.

After explaining the participant, what the user study is about, the participant will sign the form of consent and answer the questions about the person (gender, age, profession, their reason to see a physiotherapist, and if they have worn VR glasses before. Then with the physiotherapist program, a new user is added and the exercises will be recorded. So, the participants know the exercises, what would they know too in a real scenario. Because of that, the pairing of the exercises with the modalities can be random. It is important, that the exercises are named correctly in the physiotherapist program.

Then, the participants put on the VR glasses and the main program gets started. First, the participant needs to enter the ID which was told them before, then they can play around with the GUI and eventually, start with the first modality. Right after, the SUS questionnaire of the GUI will be answered, as well as the SUS and NASA TLX for the modality. Then the next modality will be tested, followed by the SUS and NASA TLX for this modality. After the last modality's questionnaire was answered, the participant is asked to rank the modalities.

9.2.2 Further Future Work

Depending on the out coming of the user study, more things must be changed and adjusted. One thing is the statistic scene. Right now, simple line charts are created with an external python script. On the chart, the user can see their accuracy of the previous exercise sessions, but we think there are more appropriate ways to visualize the data. Also, the visualization should be done within Unity and not an external program.

Furthermore, we want to move the file-based database to a SQL-alike database on a server, so the data between the physiotherapist and the patients are not only hosted local. In this database, an exercises database from and for all physiotherapists using this system we want to include. So, instead of creating all exercises, the physiotherapists could have a huge list and pick the exercises from that. The leads already to the next point on the ToDo-list: the recording of the exercises with the physiotherapist.

We introduced the possibility to record the exercises individually to take the individual agility into account. The agility should improve over the sessions and the exercises must be recorded again with the new mobility. To prevent a constant recording of the exercises, the system should be able to recognize the improvement, automatically measure the new agility and changes the data for the ghostarm.

Additionally, an artificially intelligence to detect the correctness of the exercises will be used instead of any trackers or thresholds. With this, the agility problem is also solved, because in the training database for the AI, multiple ways of doing the exercise will be present. This would work together with the exercise database, so that the AI knows every exercise which is shown to the user and also knows, if they are doing it wrong. For this, the system only would need a camera and films the movements of the user, while in real-time the AI checks about the correctness.

Most of the participants liked the idea of doing their exercises with music, but also most of them complained about the song or genre. For this, either a list of songs from different genres should be provided, or the user should be able to select a song from their own music folder. To be able to do this, in the GUI next to the music volume slider, a button which opens the explorer will be placed. If this option is liked on further studies, we can also let the user create their own playlists for the exercises.

Additional to music as motivation, we plan on using gamification for the exercises in the future. For example the exercise Apple can be surrounded by a game in which the user actually has to pick apple from a branch hanging over the user. Furthermore, a level system which gives the user further feedback on their performance should be introduced.

In this thesis, we have implemented a prototype of a multimodal motion guidance system which gives a good basis for further investigations and implementations. The system uses four modalities which were evaluated against each other. An evaluation on combinations of them can be done on the user study which will be also used to find further advantages and limitations of this prototype.

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I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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