

# **Investigating a Virtual Reality Solution for Rehabilitation in a Biomechatronics Lab and Home Environment**

JULIE MADELEN MADSHAVEN  
TONJE FJELDSTAD MARKSETH

## **SUPERVISORS**

Professor Frank Reichert  
Associate Professor Ghislain Maurice Norbert Isabwe

**University of Agder, 2020**

Faculty of Engineering and Science  
Department of ICT

Master

# Abstract

Virtual reality (VR) has emerged as a promising technical tool in physical rehabilitation. VR rehabilitation (VRR) programs, like any rehabilitation, attempt to promote neuroplasticity to improve physical rehabilitation. Research indicates that VRR is beneficial; it facilitates task-specific training, multi-sensory feedback, and diversifying rehabilitation tasks, which can motivate patients. This master thesis investigates a VR solution for a biomechatronics lab and a home-based system. This project was partially a collaboration between master students at Mechatronics and Multimedia and Educational Technology. The Mechatronics team developed a biomechatronics lab, which consists of a 6 degrees of freedom motion platform fitted with a treadmill with an integrated force plate sensors for data gathering and VR character control. Our team developed a VR solution for the biomechatronics lab and developed a home-based system using VR and a Nintendo Wii Balance Board. User tests were conducted with healthy individuals to explore if the solutions are usable and to investigate if VRR has any side-effects. Our findings indicate that VRR in the biomechatronics lab and home environment is usable, but we suggest further testing to verify these findings.

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Julie Madelen Madshaven  
Tonje Fjeldstad Markseth  
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## List of Abbreviations

<b>6DOF</b>	6 degrees of freedom
<b>CAREN</b>	Computer Assisted Rehabilitation Environment
<b>FOV</b>	Field Of View
<b>HCD</b>	Human-Centred Design
<b>HMD</b>	Head-Mounted Display
<b>SDT</b>	Self-Determination Theory
<b>SSQ</b>	Simulator Sickness Questionnaire
<b>UDP</b>	User Datagram Protocol
<b>UiA</b>	University of Agder
<b>VR</b>	Virtual Reality
<b>VRR</b>	Virtual Reality Rehabilitation
<b>WBB</b>	Wii Balance Board

# 1 Introduction

Virtual reality (VR) has emerged as a promising tool for the rehabilitation of neurological conditions, such as stroke, Parkinson's disease, and traumatic brain injury [1]. Many people with neurological conditions require rehabilitation, some in the early stages, and some regularly throughout their lives. Balance and gait issues are some of the factors which limit these patients in everyday life [2]. Generally, patients undergo conventional rehabilitation at a facility and do rehabilitation exercises at home. This can often be tedious and results in decreased motivation [3], [4]. In the last decade, research has focused on motivating by creating multi-sensory VR rehabilitation programs [5]. By using tools such as treadmills, motion platforms, and sensors, one hopes to create a more fun, effective, and task-specific rehabilitation program [6], [7].

A biomechatronics lab is under development at the University of Agder. The development of this lab is a collaboration between two fields of studies; Mechatronics and Multimedia and Educational Technology. The mechatronics team will develop the lab, and our team will create a VR solution to be used in this lab. Because of the Corona situation in Norway, our initial plan involving the development of the biomechatronics lab had to be changed. Therefore, we also created a home-based rehabilitation system using more affordable and portable devices. In this thesis, we explore if using VR is viable and a safe to use solution in a home environment. Through user testing, we hope to explore the potential of such a system. We also discuss the development and integration of the VR solution in the biomechatronics lab, as well as our findings from user testing in the lab.



**Figure 1.1:** The two motion platforms at the Norwegian Motion Laboratory [8]. The smallest platform on the left is used for the biomechanics lab.

## 1.1 Background

This master project is based on the project proposal by Assistant Professor Morten Ottestad. The project consisted of creating a multidisciplinary team to develop a biomechanics rehabilitation lab based at the University of Agder, Grimstad. The Norwegian Motion Laboratory consists of two Rexroth Stewart 6 degrees of freedom (6DOF) motion platforms. One of which will be fitted with a treadmill integrated with sensors detecting pressure and placement of weight. The project proposal concerning the VR solution consisted of creating an environment that will be displayed in a VR headset. The solution would also control the motion platform to simulate a real environment. In the future, the hope is that the biomechanics lab can be used for research, product development and rehabilitation.

## 1.2 Problem Statement

Physical rehabilitation helps people who have experienced loss of function due to illness, medical conditions, or injuries that affect their daily lives. In the rehabilitation of conditions resulting from damage to the brain, patients often do exercises in hopes of influencing

*neuroplasticity*. Neuroplasticity is the brain's ability to reorganize and optimize neural pathways to regain loss of function [9, p. 34]. Activating a neuroplastic response can be done through repetitive motion, long term practice, and task-specific training [10]. This is further evidenced by Bermudez et al. [11], who concludes that rehabilitation tasks similar to the desired activity might activate the necessary neural pathways to elicit physical and cognitive benefits.

Keeping up motivation is often difficult for patients, especially when they require regular rehabilitation exercises to generate improvements or maintain their progress. Research [1], [4] shows that VR enhances the level of adherence to rehabilitation programs, increases motivation and improves rehabilitation outcomes. A biomechatronics lab with VR allows patients to do task-specific, personalized exercises in a safe environment. By creating a holistic system, relevant data can be collected from integrated sensors, which benefits both the therapist and patient. Using VR in both a biomechatronics lab and a home-based system can be motivating and fun, and thus increase adherence to the program. However, we must assess such systems' usability, discover negative side effects, and investigate the possible VR solutions for rehabilitation before developing the system.

### 1.3 Research Questions

Based on the project proposal by Morten Ottestad and the problem statement, this research will investigate the following:

**RQ1:** How to design a VR-based solution for a biomechatronics rehabilitation lab?

**RQ2:** Will VR elicit negative side-effects on patients?

**RQ3:** Can VR be used in a home-based rehabilitation system?

Due to the Coronavirus pandemic, we had to rethink our research questions and hypothesis. Research question 3 was added when it became clear that the university would be closed down. The current situation also made us think that many people could not go to rehabilitation as usual.

From the research questions, our hypothesis is the following:

“Virtual reality (VR) rehabilitation can allow patients to do task-specific and task-varied exercises in a safe environment. Using VR in a biomechatronics lab and home-based rehabilitation system can be motivating, fun and will increase adherence to a rehabilitation program.”

## 1.4 Scope

The VR solution will be developed using the human-centred design process. It will consist of two VR environments. The user can navigate paths using either a Nintendo Wii Balance Board (WBB) at home or the biomechatronics lab's integrated sensors. The first VR environment was meant for testing if our solution could control the motion platform. Eventually, it was integrated as the first level in the VR solution, which can be used as a tutorial on how to navigate or as an easy level to do exercises in. The second VR environment was supposed to be developed after user testing of the first environment. As this iteration was not possible, we developed the second VR environment without the user's opinion. Both levels were user tested by the beginning of May. User testing on patients was not part of the scope.

## 1.5 Limitations and Constraints

On March 13<sup>th</sup>, the Norwegian government ordered a national shut-down. This resulted in closed universities all over the country, including the University of Agder. This required a change of plan for our project in case we would not have access to the university and, consequently, the Norwegian Motion Laboratory before delivering our thesis. We created a home-based rehabilitation system that was user tested. Due to the mandatory restrictions and social distancing, the sample size for this user test was small and conducted with healthy individuals. We could not test our VR solution on users in the biomechatronics lab as we intended. Instead, during integration tests at UiA, we observed and tested the system on five people related to the project.

The VR solution is intended to be displayed in a VR headset, which can be expensive. For a biomechatronics lab, this cost is not likely an issue. However, for home-based rehabilitation, the patient would be required to buy their own VR headset unless the therapist provides the VR headset. In other words, the VR headset might be too expensive for home-based rehabilitation. The solution will be developed to also run on a PC screen, if a VR headset is not available.

## 1.6 Structure of Thesis

After chapter 1 Introduction, we present chapter 2 State of the Art in VR rehabilitation. We also highlight the most relevant motivational and learning theories used in our VR solution. In chapter 3 Approach, we explain the Human-centred design process used in the planning and design of the solution. We also present and discuss our research plan. Chapter 4 Development highlights the development of the solution, the technical solutions implemented, as well as the lab setup and solution integration testing at UiA. Chapter 5 Findings and Result will present and discuss the results from the user testing, and evaluate our solutions to the requirements

from chapter 3 Approach. In chapter 6 Conclusion and Future Work, we assess our findings and suggest future work.

## 2 State of the Art

This chapter addresses the current state of the art of VR in rehabilitation, the key benefits, issues and the technical aspect of VRR as well as discovering how we can enhance the user experience, what sort of VR exercises are used in rehabilitation and lastly how experts monitor the progress of patients. We also highlight the most relevant motivational and learning theories, which are often employed when developing virtual reality solutions for rehabilitation. We focus on Ryan and Deci's *Self-determination theory, gamification* and Csikszentmihalyi's *State of Flow*.

### 2.1 Key Benefits of VR in Rehabilitation

Virtual reality (VR) opens up for the possibility of task-specific training in situations that would otherwise be unfeasible, too time-consuming or even dangerous [12]–[15]. Furthermore, it gives the patient multi-sensory feedback [5] as well as provide diverse tasks to practice. VR adds a computer-generated environment that can imitate a physical presence in which the patient can interact with the generated world while performing rehabilitation exercises. Knowing if the exercises have the desired effect and detecting progress in rehabilitation is essential both for the therapist and patient. In conventional rehabilitation, tests are used to see if the patient has progressed. In these tests, the therapist usually observes and times the patient. Some examples of tests are Timed Up and Go (TUG) and Berg Balance scale for balance and gait, Six-minute walk test, and functional reach test [16]. Kizony et al. [17] used motion capture systems and treadmills to measure progress in a VRR program by measuring parameters such as stride length, stride duration, and speed. There is a wide range of wearable sensors available that can provide data on progress. Some examples are EMGs that measure the activity of muscles, gyroscopes, and accelerometers, which can measure gait cycle and speed as well as postural imbalance [18]. Motek Medical's CAREN system [19] uses real-time sensor data to both monitor and provide feedback. They use inertial sensors, force plates, electrogoniometers, and camera-based systems to measure progress and to control the system [20]. For example, a force plate can measure if a patient has a stable center of mass, and the patient can control a character in VR by leaning to the sides.

Privacy and patient confidentiality are essential in all healthcare services, and in VRR it is sometimes a difficult field to navigate. As stated by Koenig et al. [3, p. 533], many researchers in the field of VRR simply avoid saving data to online databases. This is due to the complexity of integrating the data with the safety protocols in healthcare IT and because most eHealth applications do not employ the necessary security measures. Therefore, saving and exporting data is often done locally and not from a server. This creates unnecessary steps in terms of home-based rehabilitation, causing the therapist to export the data from the patients computer physically. Nonetheless, collecting data from the rehabilitation is es-



sential, and researchers should endeavor to do so. Metrics such as completion time, results, efficiency, and task difficulty can, for example, be written to a structured log file.

Patients who undergo rehabilitation have a goal of going back to a physically functioning everyday life, or at least a daily life where they are reasonably independent and pain-free. The road to achieving this goal often consists of many hours with a physical therapist performing repetitive movements, to increase *neuroplasticity* and strengthen the necessary muscles. This can be tedious and demotivating in the long run [3, p. 524]. Studies [7], [12] have shown that VR could increase motivation because of its adaptability, variation, and entertaining value. VR environments are experienced more as a game, rather than training and assessment, which can make the patient less anxious and self-conscious [3, p. 524].

Research on virtual reality rehabilitation (VRR) programs mainly focuses on improving the outcomes of balance, gait, motor control, and strength. Balance is the ability to keep stable and maintain postural control when influenced by forces such as gravity or movement [21], [22]. Gait relates to walking and balance where the locomotion is achieved through the movement of limbs, such as hip swing and ankle movement [6]. Motor control is the nervous system's ability to use sensory information and elicit the necessary signals to the muscles to initiate and generate movement [13], [23]. Strength is one's ability to create muscle tension to create a force [4], [24]. According to Matt C. Howard's literature review [4], and in the literature review by Porrás et al. [1], VRR programs are overall effective in developing these outcomes. Porrás et al. concludes that VRR improved balance and gait in disabilities from acute and chronic post-stroke, Parkinson's disease, multiple sclerosis, cerebral palsy, and traumatic brain injury. Especially when combined with traditional rehabilitation. In a literature review from 2019, Schiza et al. [25] focused on fully-immersive VR systems, e.g., VR headsets. They concluded that the key benefits of VR applications were the possibility of safely assessing different unsafe rehabilitation tasks, control of stimulus presentation and response measurements, and enhanced user interaction and empowerment, and the possibility of home-based rehabilitation programs.

According to the literature, using VR in rehabilitation has been established as effective, both with and without conventional rehabilitation. Howard [4] and Porrás et al. [1] found that the levels of adherence, motivation and the feeling of enjoyment were enhanced when using VR. Though researchers have shown that VR prompts enjoyment and motivation, it is still unclear if these two elements are the cause of the improved outcomes. Much is still unknown as to what are the mediating factors and mechanics that make VR effective. Further evidence is needed to establish whether the outcomes are transferable to the real world and if the level of immersion may influence the outcomes. None the less, the use of VR in rehabilitation shows promise in terms of increased positive outcomes from the training and increased motivation.

## 2.2 Neuroplasticity and VR

Neuroplasticity is the brain's ability to change throughout our lives by optimizing neural pathways. When our brain gets damaged by illness or accidents, neuroplasticity allows us to recover by reorganizing its structure and the way it functions according to our environment [9, p. 34]. In rehabilitation, one of the goals is to stimulate neuroplasticity to re-establish and rearrange neural connections. For example, patients suffering from weakness or loss of functions on one side of the body after stroke might rearrange the neural pathways which were lost through rehabilitation. According to Lawo and Knackfuß [9, p. 34], neuroplasticity only happens with the right stimulus and sustainable motivation. When utilizing VR in rehabilitation, patients can do rehabilitation exercises and have multi-sensory experiences that force the brain to create new neural pathways and cortical maps [1], [10]. VRR also facilitates for individualized training, home-based training and increased motivation which research indicate might result in increased amount of training time [26, p. 15], [1], [27].

## 2.3 VR Exercises in Rehabilitation

Most conventional physical rehabilitation involves repeated body movements, and some exercises require devices such as treadmills or weights. In VRR, we see the use of such devices augmented with VR.

The use of treadmills in gait and balance rehabilitation is a reoccurring method in VRR. Research [6], [7], [12] shows that using VR and a treadmill might have the potential to be more effective than conventional rehabilitation. Some employ the use of more advanced systems such as Motek Medical's Computer Assisted Rehabilitation Environment (CAREN) [19]. CAREN consists of a treadmill mounted on a 6 degrees of freedom motion platform and a dome which projects the virtual environment. It adds the benefit of movement of the ground, such as walking down a slope or standing on a ship at sea. It has been used in a substantial amount research [5], [14], [28] focused on rehabilitation of gait and balance issues. VRR has been used in rehabilitation of several medical issues, and the rehabilitation of both upper and lower body issues. The exercises vary between task-specific everyday activities such as street crossing [15], preparing food [3] and shopping for groceries [17] or activities such as shooting with bow and arrow [29] or popping balloons [30]. VR has become a popular rehabilitation tool because it supports the necessary repetitive practice and places it in a potentially fun and engaging environment [31]. When undergoing rehabilitation, the amount of time spent doing exercises, and doing exercises correctly determines the outcomes and progress of the patient. Patients often need home-based self-guided programs where therapists can not verify if the tasks are being done correctly, if at all. The patients also often struggle with keeping up the motivation to exercise regularly [3, p.524], which results in low adherence to self-guided programs [32]. There are many low cost tools and devices which could facilitate for in-home VRR such as Microsoft's motion capture device *Kinect* [32], [33]

or Wii balance board (WBB) [34].



**Figure 2.1:** Nintendo Wii Balance Board [35].

In the study by Profitt et al. [32], they created a home-based program with rehabilitation games using a Kinect, a monitor and a PC where 3 out of 4 participants found the program "usable" or "very usable". One issue with this program was that the patients needed to have technological knowledge to operate the system. Another tool that can facilitate rehabilitation at home is VR headsets such as the Oculus Rift, Oculus Quest, or HTC Vive. These headsets have motion tracking integrated or provided by sensors placed in the room, as well as hand-tracking with controllers. These tools enable improved home exercises and can track if the patient performs the correct movements and could be utilized to gather data on the patient's progress.



**Figure 2.2:** Oculus Rift [36].



**Figure 2.3:** Oculus Quest [37].



**Figure 2.4:** HTC Vive [38].

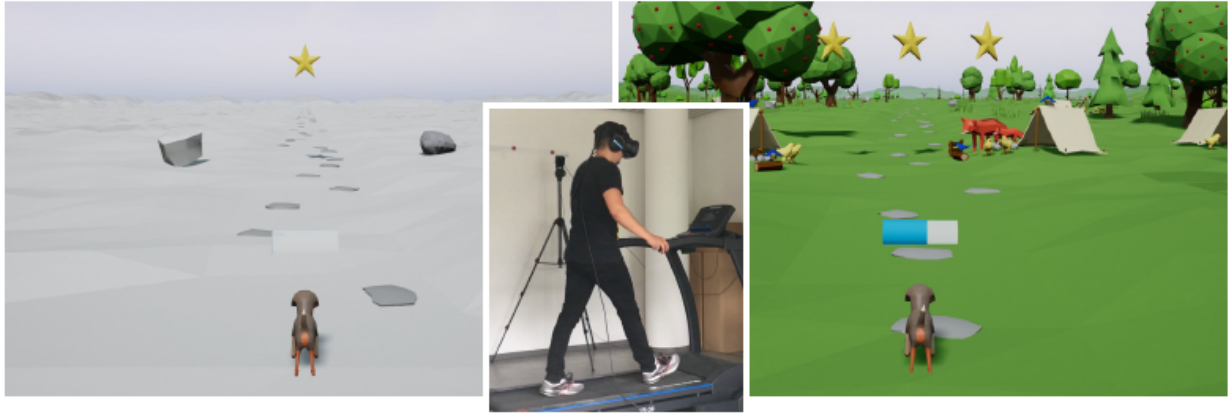
The research shows that many, if not most, conventional rehabilitation exercises are transferable to VRR. Koenig et al. [3] states that "the design possibilities for VR are literally endless and still mostly unexplored." [3, p.525]. We see the use of different equipment to display the virtual reality, and some utilize devices such as treadmills [6], [7], [17] and motion platforms [14], [39]. Sensors and games are applied to collect data and enhance the experience [40]. Some studies have focused on task-specific VR exercises. Others have created exercises immersed with fantasy and fun, and some use existing games such as the Nintendo Wii Fit games. With technology today, it is also possible to make customized home-based programs, where the goal is to get the patient to adhere to their home-exercises. The limitation of such home-based programs is that the patient needs to be technologically savvy, and the programs need to ensure usability [41, p.81]. Furthermore, there is still uncertainty about whether the improved outcomes of using VRR are indeed the VR element or that the patient naturally exercises more.

## 2.4 Enhancing the User Experience

As proposed by most of the research discussed, experiencing VR is engaging, entertaining, and contributes to increased motivation in rehabilitation. Moreover, the use of VR offers a vast amount of design possibilities [3, p. 26] which can enhance the user experience.

In Handbook of Rehabilitation Psychology [3, p. 523-524], Koenig et al. encourage more use of social interaction in VRR. Koenig et al. state that the use of social interaction could enhance the user experience and prepare patients for everyday life after rehabilitation. When going back to everyday life, patients may not be prepared for the distractions and disturbances outside. Moving cars, people talking, or loud noises are distractions that can easily disrupt the patient. By incorporating social interaction in some way in the rehabilitation, patients can get to know these distractions and be able to handle them better [3]. Social interaction comes in many forms, and implementing them in VRR could be achieved by adding features such as multiplayer mode [42], include a companion [7], or passing cars and people [3].

Kern et al. [7] created a VRR program in which they try to motivate patients to walk for more extended periods by creating a story with engaging characters. They tried to achieve autonomous motivation by incorporating competence, relatedness, and autonomy in their VRR program. The purpose of the game was to rebuild the home of a dog companion through walking on the treadmill as seen in figure 2.5. The dog walks with the patient in VR as the world around them rebuilds, giving visual and auditory feedback such as small animations, barking, and informative messages. The study concluded that using gamification elements such as an appealing storyline, reward system, and social interaction increased motivation and well-being.



**Figure 2.5:** The VRR program developed by Kern et al. [7].

Many VRR programs incorporate gamification elements in their solutions to motivate the patients. Elements such as scores, leaderboards, badges, meaningful stories, and avatars are typical gamification elements that can be implemented in VRR. Gamification will be further explained in chapter 2.7.2 Gamification.

Most head-mounted displays (HMD) and screens to display VR have integrated speakers for audio. The use of sound in VRR is commonly used for giving cues and feedback to the patient [6], [27], [30], [43]. According to British Standards Institution(BSI) report on *The Requirement for Standards in the VR and AR Sectors* [44], audio is an important aspect to improve immersion. They state that there is a need for standards regarding scene-based audio which should accurately replicate real-world audio. In other words, using spatial audio to replicate real-world audio. For example, if a bird is chirping in a tree on the right side of the user, the audio should be louder on the right side. If the user moves his head and looks straight at the bird, the audio should be received equally loud on both ears. This can produce a more compelling VR experience and can be used as a tool to guide the viewer in the VR environment. The use of music in the VR environment is also important for enhanced user experience, Keshavarz et al. [45] propose that relaxing music can reduce the risk of *cybersickness*. Cybersickness will be further explained in chapter 2.5 Issues and limitations of using VR in rehabilitation.

Furthermore, we should keep the standard usability goals in mind when developing the VR solution. These goals state that an end product should be effective, efficient, engaging, error-tolerant, and easy to learn. These will be further described in chapter 3 Approach.

In the VR solution, which will be developed, elements that can enhance the user experience will be implemented. Audio cues, points, and calming music are some of the planned features to be implemented. The solution will also utilize a HMD for full immersion into the VR environment.

## 2.5 Issues and Limitations of Using VR in Rehabilitation

Using VR in rehabilitation does have some limitations and negative side-effects which need to be considered when creating VR solutions for rehabilitation.

One phenomenon which is a known issue with VR is the risk of feeling nauseous and discomfort during and after experiencing VR. There are several terms for this phenomenon; cybersickness, simulator sickness, and motion sickness are some of them [46], [47]. These terms refer to the same phenomenon, with slight variations to what triggers the sickness and the symptoms. While motion sickness is induced by real-world experiences such as driving a car, cybersickness is induced by VR. Some of the symptoms of cybersickness are general discomfort, nausea, headache, sweating, fatigue, and eyestrain [46]. There is no clear cut answer as to why people get sick. However, three theories are prominently mentioned in research: The Sensory Conflict Theory, The Poison Theory, and The Postural Instability Theory [46].

### **The Sensory Conflict Theory**

The theory is based on the vestibular sense and the visual sense being in conflict with each other and sending information to the body, which then affects the body's motion and orientation. When the body receives visual information that it is moving, but the vestibular sense does not detect movement, there is conflict, which confuses the body and induces symptoms. As mentioned, the theory has some problems. It is unpredictable. There is no answer to why some get sick while others do not from the same experience. It has no explanation as to why the conflict between the vestibular and visual senses causes sickness.

### **The Poison Theory**

The Poison Theory is based on how the body reacts when ingesting poison. When ingesting poison, the different senses are affected and send a warning to the rest of the body to remove the stomach's content. With VR, the vestibular and visual senses are affected, and the body reacts like it has ingested poison. Like The Sensory Conflict Theory, this theory is unpredictable as well.

### **The Postural Instability Theory**

The Postural Instability Theory is based on a primary behavioral goal; maintaining postural stability. Sudden changes in the environment cause postural instability and result in symptoms of cybersickness. Being in postural instability for an extended period of time will cause more severe symptoms of cybersickness. In VR, the scene can change swiftly and, therefore, cause symptoms of cybersickness.

Although we do not know precisely why cybersickness occurs, we do know that multiple factors trigger cybersickness. Human, task-related and technical factors must be considered when creating VR solutions according to LaViola [46] and Davis et al. [47]. Lag, resolution,

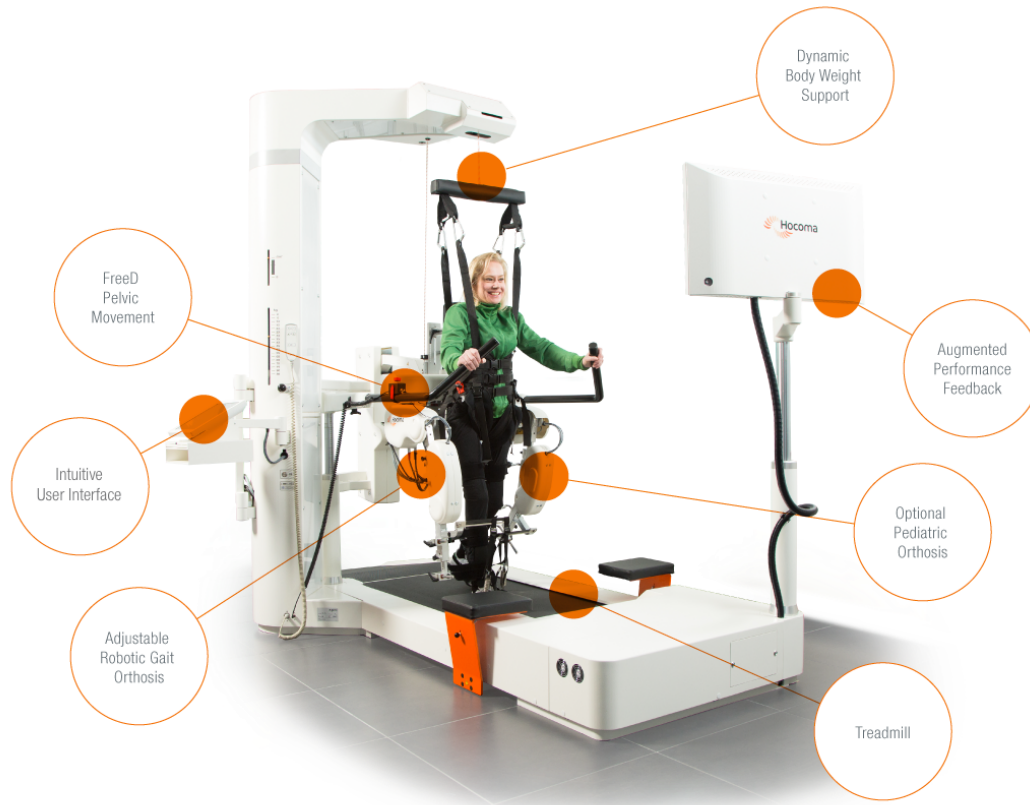
flickering, and motion tracking are all technical factors that might trigger cybersickness if not optimal. Human factors to consider include age, gender, posture/position, and illness. Some of the task-related factors are duration, navigation, and control.

Utilizing the best hardware could reduce the chance of cybersickness, as factors such as resolution, lag and frame rate play an important role in avoiding cybersickness. The technical aspects of VR will be further discussed in chapter 2.6 Technical aspects of VRR. The duration of the VR sessions should not be too long, as being immersed in VR for prolonged periods of time can trigger cybersickness. Sinitski et al. [48] tested thirty healthy people from the Canadian Armed Forces. The study showed that some of the participants experienced simulator sickness, with symptoms like headaches, dizziness, eyestrain, and difficulty with focusing, after 45 minutes of immersion. This is quite a lot of time, and evidence suggests that exposure should be kept under 15 minutes to limit cybersickness [49]. The VR headset producer Oculus recommend taking 10-15 minute breaks every 30 minutes, and taking more frequent breaks if prone to cybersickness [50]. Research [51], [52] has also shown that navigation in VR affects cybersickness. Teleportation has been demonstrated to elicit the least amount of discomfort, while navigation using touchpads, keyboards or joysticks results in higher risk of cybersickness [51].

There are proposed measurements that may serve as an indicator of cybersickness [53], such as heart rate, respiration, and skin temperature, all of which can be monitored using the appropriate sensors. To measure sickness, some researchers use a questionnaire called Simulator Sickness Questionnaire (SSQ) created by Kennedy et al. [54] in 1993, which is usually a pen and paper questionnaire but can also be conducted verbally. Some researchers choose not to use SSQ, stating that it is more appropriate for correlation analysis than measuring illness [55].

The safety of the patients while in VRR is essential. In the study by Sinitski et al [48], the participants wore a harness to prevent them from falling. The safety of the patient must always come first, as well as proper security. In VRR the patient does not necessarily have control of what happens outside of the VR environment, so the feeling of security is essential for successful rehabilitation. In a study by Brüttsch et al. [12] they tested and compared the effect using a gait orthosis Lokomat with and without VR. They tested it on children with gait disorders and a control group of healthy children. The study had some limitations, one of them was the safety feature. The treadmill was equipped with a force monitor that would stop the treadmill and all other operations if too much pressure was put on the treadmill. This caused issues with the measurements since the healthy children put more pressure on the treadmill than those with gait disorders.





**Figure 2.6:** The gait orthosis Lokomat [56].

When applying the use of VR in any type of health-related context involving patients, it is critical that the patients do not experience discomfort as this might lead to negative interference in the treatment. Many of these issues and discomforts can be avoided by taking necessary steps, while some are difficult to solve because of human factors such as susceptibility to cybersickness. Some issues revolving around usability for therapists can be solved by creating software that is easily adaptable by therapists. However, this requires the necessary time frame to develop it. For the biomechanical rehabilitation platform, which is being developed at UiA, the patient will be secured with a harness. In a home-based system, the use of HMDs might be unsafe because of the risk of falling. This potential safety issue will be user tested and discussed further in chapter 5 Findings and Results.

## 2.6 Technical Aspect of VRR

As mentioned in chapter 2.5 Issues and limitations of using VR in rehabilitation, one crucial factor to consider in VRR is technology. In this project, the tools which will be utilized in the biomechatronics lab have already been determined. At the same time, in the home-based rehabilitation solution, we are free to choose from the university's available tools.

Nonetheless, it is important to know the tools used in VRR and to understand the advantages and disadvantages. Furthermore, how to offer the best user experience while minimizing the risk of adverse effects.

Kourtesis et al. [57] examined different types of technology used in VRR and the qualities these required to offer the best user experience. They found that if using a HMD it must have a good quality screen, adequate resolution, refresh rate, and field of view (FOV). FOV is the area which is captured by the display device, the size of FOV directly affect image quality. Their results generated some technical standards of HMDS;

<b>Feature</b>	<b>Suggested standard</b>
Display screen	Good quality (OLED or upgraded LCD)
Display resolution	minimum 960 x 1,080 sub-pixels per eye
Refresh rate	no less than 75hz
Field of view	no less than 110 degrees

**Table 2.1:** Suggested technical standards of VR in rehabilitation.

These standards are suggested to preserve the health and safety of the patients and to get reliable results from user testing. Kourtesis et al. [57] also recommend the use of external hardware to enhance the experience, fast and accurate motion tracking, spatial audio, and ergonomic interactions. The standards of the computer running the VR must meet the minimum requirements of the VR software and HMD. Most new generation HMDs all appear to possess the hardware characteristics, offering a more natural and comfortable VR experience.

In a review by Rebenitsch and Owen [55] the use of different displays was studied. The display study review found that choosing a display for VR comes down to how it is going to be used. Does the VR require the patients to move their heads? How immersive should it be? They looked at this in relation to many different types of displays; HMD, large screens, and computer-aided virtual environments (CAVEs). Using large screens and CAVEs in VRR increases the chance of the patient experiencing symptoms of motion sickness. This is because these types of displays have a larger field of view than HMD. Using HMDs in VRR might also cause cybersickness, but it gives the benefit of the user being more in control. And as stated in chapter 2.5 Issues and limitations of using VRR in rehabilitation, taking some precautions can minimize the risk of cybersickness. Rebenitsch and Owen [55] also looked at rendering mode studies. When rendering a VR, the virtual display and the physical display should be the same size, as differences in size can affect cybersickness. There are three rendering modes: monoscopic, bi-ocular, and stereoscopic. Monoscopic rendering uses one viewpoint to display one image and direct it to one eye. Bi-ocular uses one viewpoint to display two overlapping images, one image broken into two by cropping a section of the image from the

viewpoint and directing it to the corresponding eye. Stereoscopic rendering uses two images from different viewpoints. In the review, they found that bi-ocular rendering had the least strain on the eyes, which is what most modern HMDs utilize today.

The University of Agder owns three different VR headsets; The Oculus Rift, Oculus Quest, and HTC Vive. The table below details the specifications for the available devices.

Feature	Oculus Quest	Oculus Rift	HTC Vive
Display resolution	3200x1440 OLED	2160x1200 OLED	2160x1200 OLED
Refresh rate	72Hz	90Hz	90Hz
Field of view(degrees)	Hor: 94 Vert: 93	110*	Hor: 110 Vert: 113
Requires external sensors	No	Yes	Yes
Requires external computer	No	Yes	Yes
Can be used with glasses?	Yes	Yes	Yes
*Cannot find vertical FOV			

**Table 2.2:** Comparison of features on Oculus Quest [58], Oculus Rift [59], [60] and HTC Vive [61].

The HTC Vive meets most of the standards suggested by Kourtesis et al. [57], though it requires external sensors to be attached to the ceiling. The Oculus Rift also requires external sensors, which are placed on a table close to the player. The Oculus Quest does not have the optimal refresh rate or the appropriate field of view, but it requires no external sensors and can be developed to be utilized wirelessly.

The use of treadmills is a reoccurring method when it comes to gait training. Shema et al. [6] utilized a treadmill with a motion tracking system in their 5-week treadmill training program. The motion tracking system utilized in the study captured the movement of the feet and sent it to a computer that created the virtual environment. The VR environment was displayed on a flat-screen, where the patient saw a footpath with obstacles such as puddles and hurdles that required the patient to either increase their step length or move to the side to avoid crashing. The patients regarded the training as highly engaging. They reported higher motivation, and they had 95% patient adherence to the program.



**Figure 2.7:** The VR environment and tools from the 5-week treadmill program by Shema et al. [6].

Much in the same way, Kern et al. [7] utilized motion trackers and a treadmill in their study on increasing motivation in gait training. Instead of using a screen, they used a HTC Vive, which is a HMD, to display the VR environment. They evaluated the well-being of the participants in the study by looking at user satisfaction, anxiety, and simulator sickness. The results revealed that the participants in the VR condition showed higher levels of well-being than those in the Non-VR conditions.

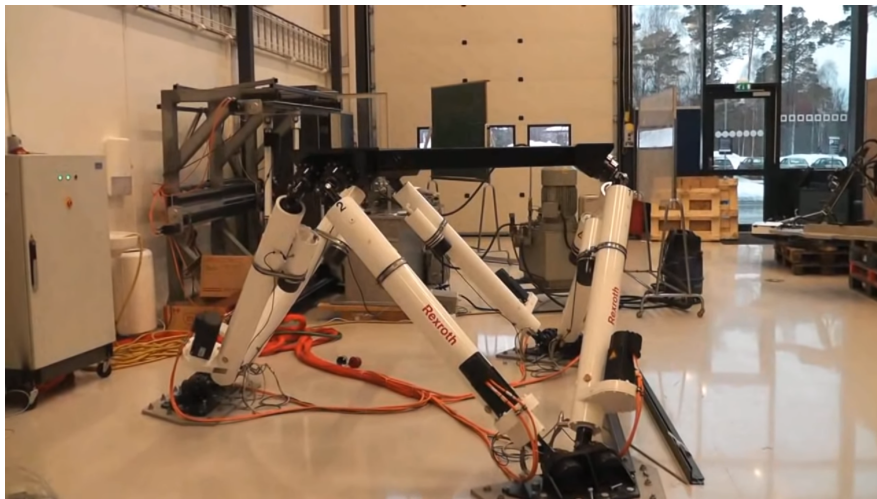
Borghese et al. [27] conducted a study in which the participants played two games; "Fruit Catcher" and "Animal Feeder". They tracked the movement of the hands using Microsoft's motion capture system Kinect in the game "Animal Feeder". In "Fruit Catcher" they utilized a Nintendo Wii Balance Board (WBB), which the participants stood on and applied pressure by leaning to control the character in the game. Their research objective was to describe a game engine that had all the necessary characteristics to facilitate home-based rehabilitation. They found that their system did indeed support rehabilitation at home and that the Kinect and Wii Balance Board were usable in such an environment. In our home-based prototype, the Wii Balance Board will be utilized with an Oculus Quest. A usability test of these two tools together will be further discussed in chapter 3 Approach and chapter 6 Conclusion and Future Work.

The well-known biomechatronics lab, CAREN, utilizes a dual-belt treadmill mounted on a motion platform with 6 degrees of freedom(6DOF). It is surrounded by 6 3D motion capture cameras, which tracks movements and creates a Human Body Model with the help of markers placed on the user [39]. A cylindrical display is used to display the virtual environment to provide the user with 180 degrees FOV. [48].



**Figure 2.8:** Screenshot of Motek Medical CAREN [62].

The lab, which is being developed at UiA by the mechatronics team consists of many of the same tools as in the CAREN lab; 6DOF motion platform, 18 motion capture cameras on the walls, as well as a force plate, integrated treadmill. Much of the difference between CAREN and the biomechanics lab at UiA will be how these tools will be utilized and a head-mounted display will be used to display the VR.



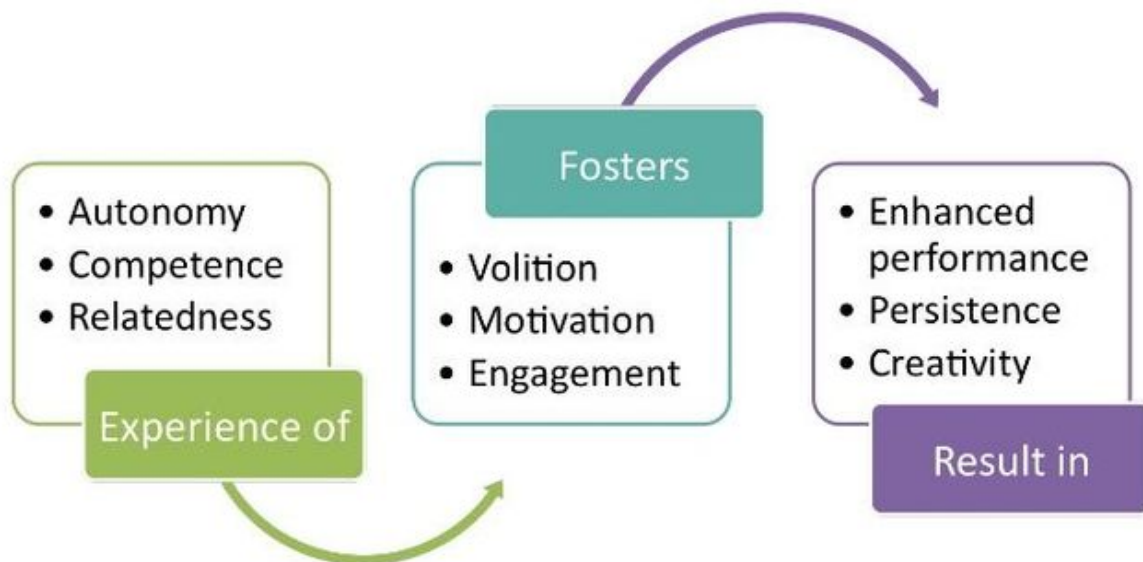
**Figure 2.9:** The motion platform at the University of Agder which will be utilized for the biomechanical lab [63].

## 2.7 Motivational and Learning Theories

### 2.7.1 Self-determination Theory

Self-determination theory (SDT) [64] is a macro theory of human motivation that concerns people's inherent tendencies towards psychological growth and development. Ryan and Deci [65], [66] defines three needs that, if experienced, enables optimal growth: *competence*, *relatedness* and *autonomy*. Competence relates to people's inherent desire to feel that they are effective and have the necessary skills to produce the desired outcome. People want to feel that they are competent, which enables them to engage in challenging tasks to test and increase their skills. Relatedness is the need to feel a sense of belonging; people need to care about and be cared about by others. Autonomy is people's need to feel that they have control of their destiny, to be allowed to act by their own volition in unison with their internal self.

When people experience these three factors, they can achieve intrinsic motivation [66]. Initially, the theory differentiated between intrinsic and extrinsic motivation but has now been adapted to autonomous and controlled motivation.



**Figure 2.10:** Illustration of the benefits Self-determination theory [67].

#### Autonomous motivation

This type of motivation comes from internal and external forces that align with the person's sense of self, such as the possibility of reaching a life goal. People inherently have a natural

inclination for exploration, mastery, and curiosity, driven by nothing but the enjoyment of doing a task. Autonomous motivation is arguably the best type of motivation, but it is not always possible in every situation.

### **Controlled motivation**

Controlled motivation comes from external regulation. It is a reward-driven motivation by factors such as money, fame, or praise from others. This type of motivation can be useful and may be suitable for specific situations, such as seeing improvement in your rehabilitation in the form of a score.

Research [68] has shown that people who do tasks with controlled motivation have their energy depleted, while when they experience autonomous motivation, the energy stays the same or might even increase. When patients practice rehabilitation programs, prompting autonomous motivation, although easier said than done, would be most beneficial. Though any motivation is better than none, and controlled motivation can be powerful when used correctly.

### **2.7.2 Gamification**

Gamification is taking motivating game design elements from games and applying them to non-game contexts. The goal is to motivate change in behavior or mindset [69]. Points, badges, leaderboards, performance graphs, meaningful stories, avatars, and teammates are some of the most commonly used game design elements and are easily manipulated [70]. Motivational research shows that six principal perspectives are relevant to gamification: The trait perspective, the behaviorist learning perspective, the cognitive perspective, the perspective of self-determination, the perspective of interest, and the perspective of emotion [70]. In [70], they focused on the self-determination perspective because it contains various motivational mechanics, and it encompasses some of the other principal perspectives. Within the self-determination perspective, there are three psychological and intrinsic needs; these needs are mentioned in chapter 2.7.1 Self-determination theory as the need for competence, autonomy, and relatedness. These needs are motivational assets that could be used to modify the environment. Feedback from the game elements induces these needs. Gamification has gained a lot of interest over the years and has been implemented in various fields, such as in education, health and wellness and in social networks [71]. In [40] Sardi et al. reviewed studies on strategies on how to implement gamification in eHealth and the benefits and disadvantages such an implementation could impose. They found that the use of gamification in healthcare is sparse because implementing it is both critical and demanding. They also found that gamification induces engagement, immersion, enjoyment, and had a positive change in behavior. There are also some challenges with gamification. Motivation and engagement

from gamification are not sustainable that the effect will fade after a while. This might be because gamification often uses elements that affect controlled motivation. Placement and use of the game design elements should be weighed very thoroughly, as wrongly placed game design elements could confuse the user [40].

### 2.7.3 The Flow State

VRR often combines the concentration needed to perform rehabilitation exercises correctly and the enjoyment experienced in the virtual environment. One could argue that VRR usually has some form of play or game elements, which, when integrated with what is perceived as work, can sometimes place the user in a psychological state called flow [72]. Flow, also known as being *in the zone*, refers to a state of mind where one is experiencing concentration and enjoyment. Jackson and Csikszentmihalyi [73, p. 20-33] postulate that nine dimensions together represent the optimal state of flow:

1. **Challenge-skill balance**

The balance between challenge and skill needs to be equal. If the challenge is too difficult, you get frustrated or anxious. If its too easy, you get bored.

2. **Action-awareness merging**

The merging of body and mind: being completely absorbed by the task without thinking of activities outside of the task.

3. **Clear goals**

Having a clear purpose and goal of the task at hand.

4. **Unambiguous feedback**

Unambiguous feedback refers to providing clear feedback regarding task performance. Getting immediate and clear feedback allows for adjustments that get you closer to your goal.

5. **Concentration on task**

Concentration narrows our attention and focuses on the task, excluding distractions. Complete concentration is “one of the characteristics of optimal experience mentioned most often” [73, p. 25]

6. **Sense of control**

A sense of complete control without fear.

7. **Loss of self-consciousness**

Loss of self-consciousness gives you a feeling of enjoying the experience without fear, self-doubt, or concerns.

8. **Time transformation**



Feeling as though time has stopped, sped up or slowed down.

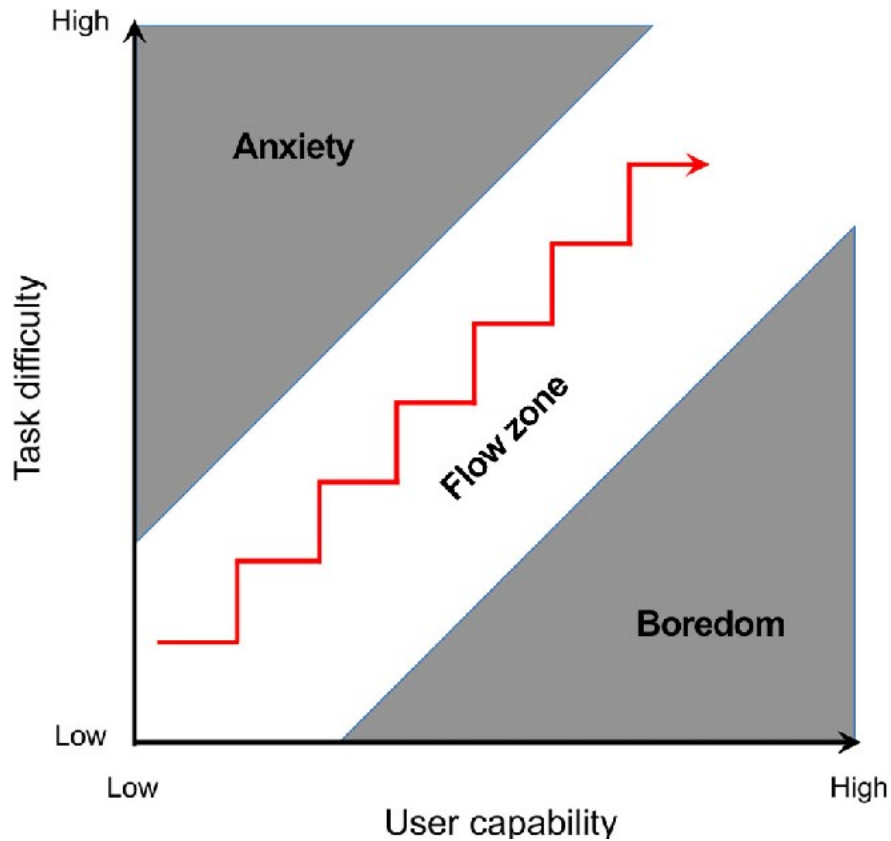
### 9. Autotelic experience

When a task is autotelic, it is an activity you do for your own sake: it is intrinsically rewarding.

In VR, you are naturally almost entirely immersed in an environment that gives a sense of complete involvement, which one could argue can lead to flow. The nine dimensions above have analogies to video game enjoyment and factors which should be considered when developing VRR solutions.

One element which is often mentioned in relation to VRR is the possibility of adjusting the difficulty of the task to the user's skill [1], [5], [13]. Adjusting the difficulty can make the experience more enjoyable and motivating without getting the user stressed, which causes self-doubt, fear, and loss of confidence. Keeping the balance between *challenge-skill* is principal in VRR.

In rehabilitation, the willingness of a patient to stay engaged depends on the perceived treatment benefits [74]. Hence the *goal* of the VRR should be clear to the patient, with explicit explanations of the benefits that can be achieved through the exercises. Since information about progress is essential in reaching this goal, in-game feedback about progress and the current level is also essential. Another element of flow is *sense of control*; in VRR, the patient should know how to interact correctly with the VR environment.



**Figure 2.11:** Model of the flow state [75].

### State of the Art Summary

To summarize, research indicates that VRR is beneficial. The use of VRR can facilitate task-specific training, which would otherwise be too time-consuming, dangerous, or unfeasible for other reasons. In addition, it offers multi-sensory feedback to the patient and diverse practice tasks. VR benefits from gamification, and motivates the patients to adhere to the rehabilitation program. Patient safety must always come first in rehabilitation, and should always be thoroughly considered before employing the use of VR in rehabilitation.

## 3 Approach

In this chapter, we present the methods applied in the Human-Centred Design approach. We also present the research approach and the plan for the usability testing of the home-based system.

### 3.1 Method

#### 3.1.1 Qualitative Data Gathering

Qualitative research methods are used to understand the reasons behind the action people makes, their opinions and motivations. This is mainly achieved through interviews, observations, and questionnaires. It is often used when investigating a new field of study, or to theorize and uncover prominent issues. It is expressed in words rather than numbers and can consist of smaller sample sizes, whereas quantitative research usually consists of a larger sample size. In quantitative research, one investigates by gathering quantifiable data, often presented in a statistical way. In a usability test, we conducted interviews, observations, and utilized questionnaires which is a qualitative research approach. Consequently, to understand how the user might interact with the system and uncover potential issues with our VR solution [76, p. 270].

#### 3.1.2 Avoiding Bias

As with most research, there is a risk of bias. One potential bias when involving users is that most people naturally want to please or seem intelligent, resulting in insufficient or faulty data. To avoid this, interviewers should be careful how they phrase their questions [76, p. 230]. For example, "You seem like you had no issues with controlling the character..." might make the participant answer that this was true not to offend the interviewer. There is also a possibility that participants forget what happened or what they answered previously. For example, in a Simulator Sickness Questionnaire which is answered before and after testing, it is easy to forget your previous answer. It is not possible to avoid this, but it is important to be aware of it and carefully plan the questions [76, p.233].

The interviewer must also consider body language, as this can have a strong influence on the participant. In our interviews, we tried to mix question types and not phrase them so that the participant would be influenced to answer positively or negatively. We also tried to keep a professional, open, and friendly body language giving the participant time to think and answer in their own time.

### 3.1.3 Testing and Evaluation Methods

There are many ways of evaluating a product, system, or solution, and there are two main types of evaluation: expert-based and participant-methods [41, p. 215]. The evaluation methods depend on the types of data that will be collected and the questions that need answering. The method chosen for evaluating can give more information on if the product meets the requirements and how well it meets them.

When evaluating a product, it is necessary to choose the correct setting where the evaluation will be conducted. The setting will depend on what will be tested and observed. There are three settings for evaluation: controlled environment, natural environment, and any settings which do not involve users [76, p. 437]:

1. **Controlled environment**

Controlled environments usually consist of a laboratory where the product is tested to determine its usability, test hypotheses, and observe user behavior. All participants usually have the same experience, and the observers have more control over the testing. Controlled environments allows for *direct observation*.

2. **Natural environment**

The natural environment is the intended location in which the product would be used. This environment is good for capturing how a product would function in its intended location. For example, in online communities or public places.

3. **Settings without users**

Settings without users utilize researchers, experts, and consultants to critique, predict, and model features of the interface to pinpoint usability problems. Inspections, walk-throughs, models, analytics, and heuristics are some of the methods used to pinpoint usability problems. This type of environment is usually cost-effective but might not reveal usability issues.

There are pros and cons to each environment. For example, controlled environments work well for discovering usability problems but are not best suited when trying to discover the context of use. Natural environments are useful for discovering how people would use said technology, but conducting user testing in this environment could be expensive and challenging to execute. Settings without users are cheap and quick to conduct but can miss important usability problems [76, p. 437].

## Observation

Observation is a natural part of testing a product. Observing how users interact with a product can yield valuable insights, and help developers understand their users and how

they might use the product. In observation in a controlled environment, the participants are usually informed of the research aim and know they are being observed, and the researcher usually films the session and writes notes. Clayton Lewis and John Rieman developed and introduced the *Think Aloud* method [77], which is a data-gathering method and is perceived as one of the most commonly used methods in usability testing. It is easy to use the Think Aloud method, as you only need to inform the user that they should express in words what they are doing, finding difficult, thinking, or feeling. The Think Aloud method gives an understanding of where the user encounters problems or finds something difficult. Though there are some drawbacks to this method since it feels unnatural to say everything that comes to mind, and it is easy to forget to speak.

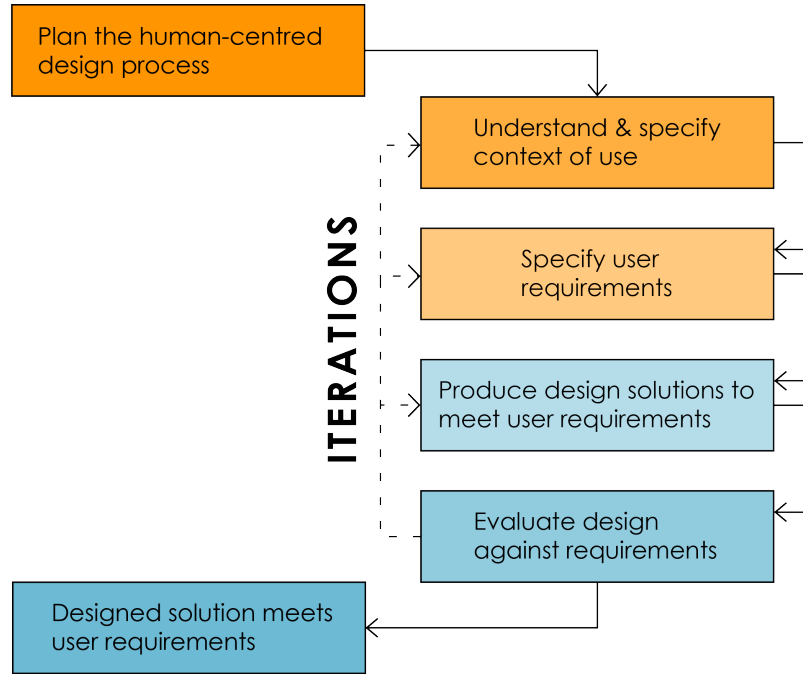
## Interviews

Interviews can be used to elicit the user's opinions about an experience, product or solution. When it comes to conducting an interview, there are mainly three ways to do so: structured, semi-structured, and unstructured interviews. For *structured interviews*, sets of questions are made, and the interviewer adheres to those questions. In structured interviews, the study participants are all asked the same questions in the same order, which makes it easier to compare answers in a study. In an *unstructured interview*, usually, there are no preplanned questions. This type of interview is conducted when there is little background information and to reduce preconceptions [41, p. 142-143]. Unstructured interviews are often used when collecting data as a start and continue the conversation about a topic, for example gathering knowledge of the respondent's career, work, or field of expertise. *Semi-structured interviews* are a combination of structured and unstructured interviews. Sets of questions are developed beforehand, but the interviewer can rephrase them, ask follow-up questions, allow new ideas and further knowledge to be discovered, and provide an opportunity for the respondents to explain and give reason their answers. It provides a clear set of instructions, but allowing for open-ended questions and further elaborations on a topic and can offer reliable and comparable qualitative data. In interviews, the data from open-ended questions are often analyzed as qualitative data, while data from closed-ended questions are analyzed as quantitative data [76, p.273].

## 3.2 Human-Centred Design

There are many approaches to designing a usable interactive system. One popular approach is Human-Centred Design (HCD) [78]. HCD approach focuses on applying human factors and using the system to create interactive systems more usable. The goal is to fulfill the user's needs and requirements [78]. According to Maguire [79], HCD has four key principles: "(1) The active involvement of users and clear understanding of user and task requirements, (2) An appropriate allocation of function between user and system, (3) Iteration of design

solutions, and (4) Multi-disciplinary design teams” [79, p. 588-589]. To implement the usability requirements for the interactive system, they go through an iterative process until a specific usability requirement is achieved. In figure 3.1 the iterative process is illustrated.



**Figure 3.1:** The Human-Centred Design Activities, adapted from [78].

### 3.2.1 Plan the Human-Centred Design Process

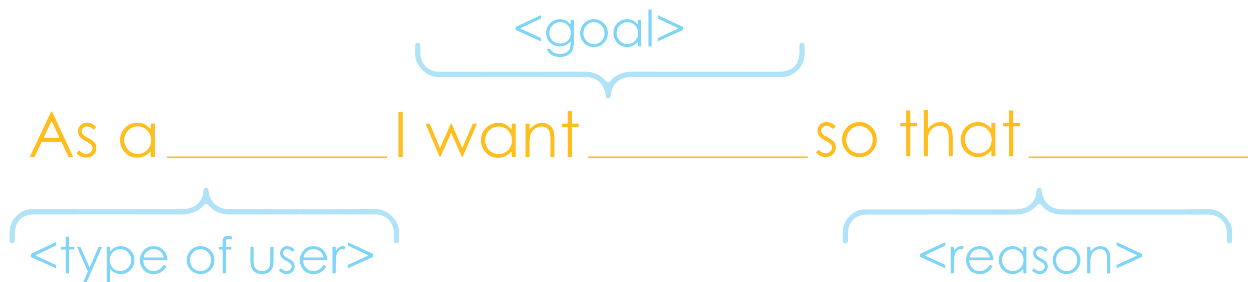
For the Human-Centred Design (HCD) approach to be successful, it is essential to develop a good plan and follow it throughout the project, from start to finished product. According to ISO standard 9241-210:2019 [78], when planning a project, it is necessary to look at the importance of human factors and ergonomics by evaluating how usability is related to the purpose and use of the system (e.g., health and safety issues, numbers of users, size). These risks can result from poor usability (e.g., financial, safety, acceptance), and the project’s development environment (e.g., size of the project, time frame, range of technologies).

To plan the HCD approach, we looked at different methods and resources to apply in all the activities. We also looked at how much time should be allocated to each activity and found effective ways to communicate and document our findings.

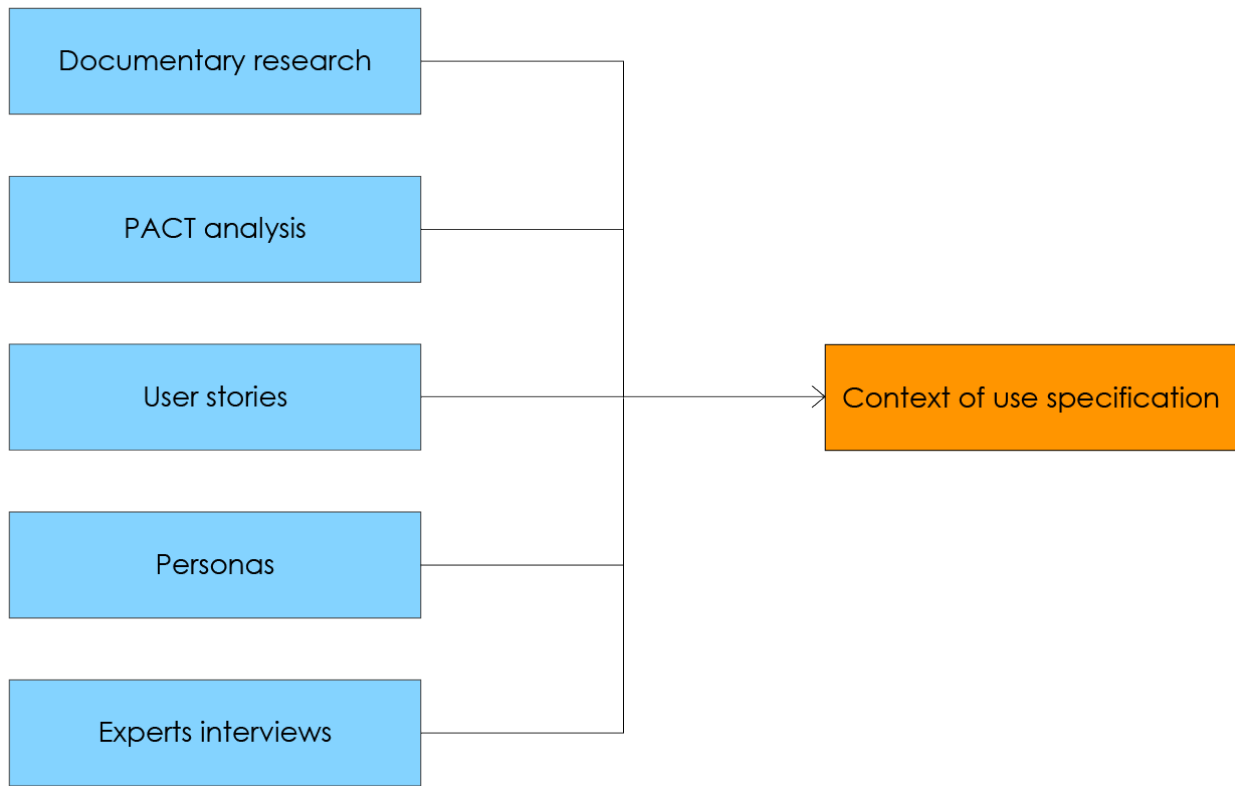
### 3.2.2 Understand and Specify the Context of Use

Collecting relevant information, such as user characteristics, tasks, and environment, is essential to understand and specify the context of use [78]. There are multiple ways to collect

this information. For this project, we looked at previous studies, which can be found in chapter 2 State of the Art, conducted a People, Activities, Contexts, and Technologies (PACT) analysis, developed personas and user stories, and interviewed experts. The PACT analysis is a framework for thinking about human-centred design and helps to understand the users and how they will use a product [41, p. 25]. To represent the different kinds of users which the product is developed for, personas are created. Name, age, goals, and background are some of the characteristics that a persona should include [41, p. 55]. User stories are short and simple written narratives that describe one activity of a single user or situation [80]. The sentence structure of user stories is illustrated in figure 3.2.



**Figure 3.2:** Sentence structure of user stories, adapted from [80].



**Figure 3.3:** Context of use specification.

## Interviews with Experts in the Field of Rehabilitation

Our team has a background in technology, not in rehabilitation, so to develop a usable VR rehabilitation system, it is essential to know what is utilized today. What types of rehabilitation exercises experts believe could be performed in such systems and their general opinions of the development of such a system. For this research, semi-structured interviews with two experts in their field were conducted. The first interview was with a professor at the Department of Sport Science and Physical Education at UiA, who works closely with many stakeholders in the field of sports and health. This interview was a preliminary interview to explore the area of VRR and determine the usefulness of such a system. Later in the process, an interview with two experts working within the field of rehabilitation was conducted. The goal was to determine what tools they use today, what types of exercises they envision could make use of a biomechatronics lab, and their general thoughts. Both of these interviews would help us gather requirements for the system. The interviews are displayed in Appendix A.

### 3.2.3 Specify User Requirements

According to Maguire [79], analyzing user requirements is the most crucial part of development. For this project, some of the technical requirements were already set by the mechatronics team. Nevertheless, to set the user requirements for this project, we used James and Suzanne Robertson's *Volere Requirements Specification Template* [81]. This template separates the requirements into two categories. The *Functional requirements* describes how a product should work, which processes actions has to make, and what rules to follow. The *Non-functional requirements* describes usability and performance in the product. There are many ways to capture and maintain the requirements, we used Volere's snow card, which we have modified, as seen in figure 3.4.

<b>Requirement #:</b> 1	<b>Requirement Type:</b> 9	<b>Event:</b> 1
<b>Description:</b> The product should display a landscape with bumpy roads and slopes		
<b>Rationale:</b> To be able to train balance for users who experience balance issues		
<b>Originator:</b> Software developer		
<b>Fit Criterion:</b> The user will navigate over these bumps and slopes in the road, and they will be able to feel them		
<b>Customer Satisfaction:</b> 5		<b>Customer Dissatisfaction:</b> 5
<b>Priority:</b> 1	<b>Conflicts:</b>	
<b>History:</b> Created March 9th 2020		

**Figure 3.4:** Screenshot of a User Requirement.

From the interviews with experts, PACT analysis, personas and user stories, found in ap-



pendix A, B and C, we developed a set of requirements. These requirements are listed in Appendix D and Appendix E.

### Usability and User Experience Goals

Usability is defined in [78, p. 3] as: "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency, and satisfaction in a specified context of use." According to Benyon [41], there are five usability goals: *Efficiency, effectiveness, learnability, safety and utility*. But, according to Sharp et al. [76, p. 19], there are six goals. The sixth goal is: *memorability*. The usability goals is displayed in the inner circle of figure 3.5. One way for the designer to assess the interactive product and the user experience is to utilize usability goals as questions. With usability questions, getting information about problems with the design early on in the process is possible. Another way is to turn usability goals into usability criteria and assess how a product can improve user performance. The most used usability criteria are the time to complete, the time to learn, and the number of errors. However, this type of testing does not view the quality of the user experience [76, p. 19, 23].



**Figure 3.5:** Usability Goals and User Experience Goals [82].

User experience is defined in ISO standard 9241-210:2019 [78, p. 4] as: "user's perceptions and responses that result from the use and/or anticipated use of a system, product or service."

User Experience goals are different emotions and felt experiences that can be either desirable or undesirable. Some of the desirable emotions and feelings are shown in the outer circle of figure 3.5. Just like the usability goals, the user experience goals are more practical when phrased as questions [76, p. 23-24].

### 3.2.4 Produce Design Solution to Meet Requirements

After finding the context of use and setting the user requirements, it is time to start designing. Interactive design has two sub-categories, *conceptual design* and *physical design* [41, p. 188]. Creating an interactive system that is understandable is central in conceptual design. Conceptual design focuses on the functions, logic, structure, and content, to ensure that the system is easy to learn by users, fit their expectations and preferences. Physical design [41, p. 202] focuses on how the system will look, how to use it, and how it will behave. With physical design there are two key design ideas, *design languages* and *interactive patterns*. Design language consists of design elements, rules for how the design elements work together, and in which context to use them, and which rules to follow [41, p. 203-204]. Interaction patterns are similar to design guidelines but with better descriptions and examples [41, p. 206].

We started by creating a *Conceptual model*, which is illustrated in figure 3.6. The model shows the structure of the VR system. The orange color represents what the user can do, and the blue color represents what the system can do.

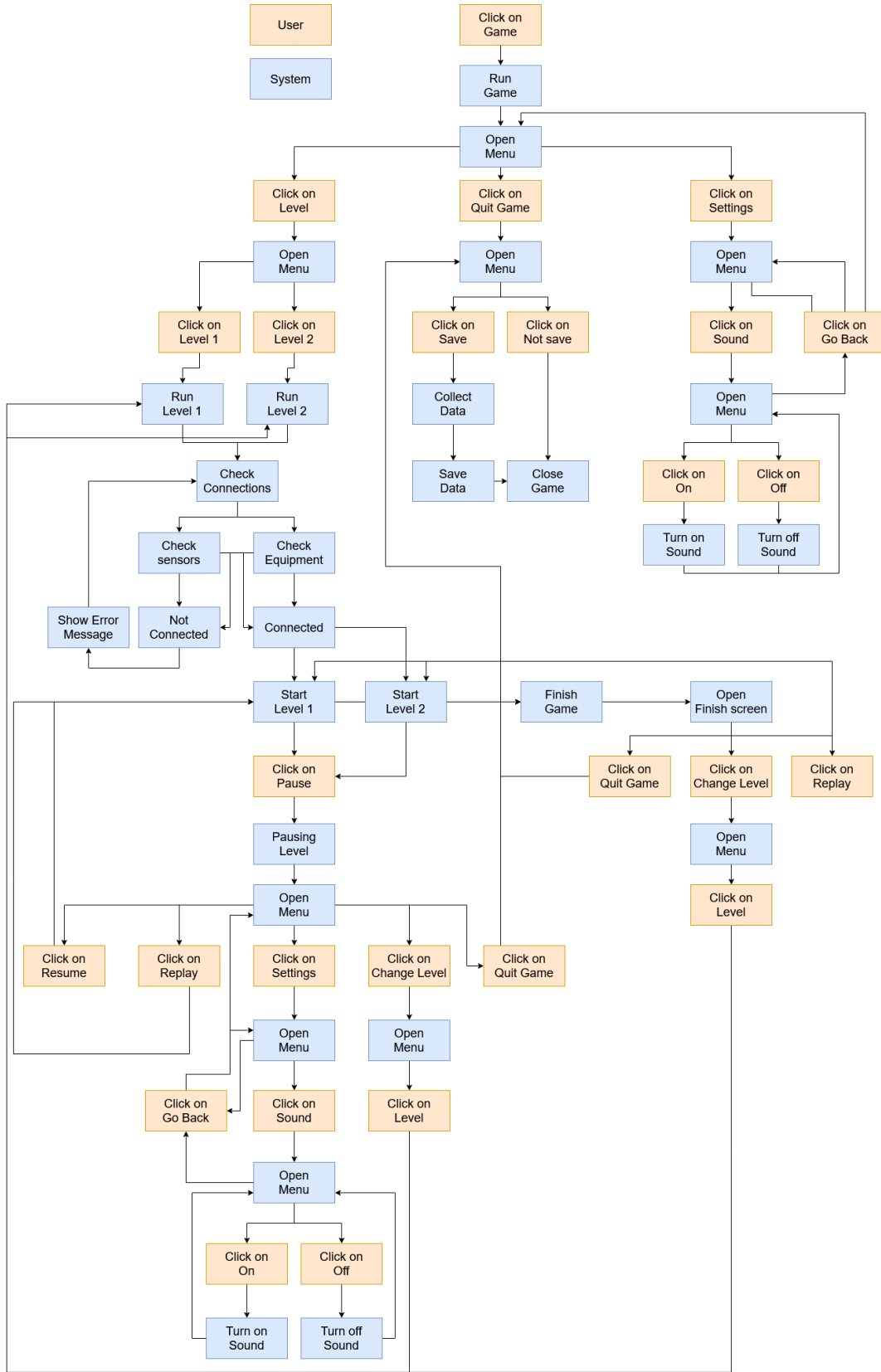


Figure 3.6: Conceptual Model.

After completing the conceptual model, we had to think about the visual design of the system. We came up with three potential scenarios, boat on the water, snowboard downhill, and skateboarding through a city. We decided on, in agreement with the mechatronics team, to develop the skateboarding scenario. When designing a product it is usual to create prototypes, there are two main types of prototyping: *low-fidelity(lo-fi) prototypes* and *high-fidelity(hi-fi) prototypes* [41, p. 176-177]. Low-fidelity prototypes are usually made with paper, hence the nickname paper prototypes. A lo-fi prototype is easy and quick to make to test early design ideas and look at the function, structure, and navigation of the design idea. Since the prototype is made of paper, there are some issues: *robustness, scope, instructions, and flexibility*. Paper is fragile and could tear easily during testing. The prototype should focus on key elements and not be too detailed. The instruction must not be overbearing, and it should be possible to make adjustments during testing. Hi-fi prototype is made with software to mock up interactive effects easily. A hi-fi prototype is created to evaluate the design elements and to get acceptance. However, this could also cause problems. People can believe that it is the final product and that the prototype suggests that the system can be implemented.

Because of the time frame, instead of creating a lo-fi paper prototype to test on users, we created rudimentary sketches that helped us understand and design a high-fidelity prototype. It was important early on to conduct a communications test with the mechatronics team, to move both projects forward. This is why it was necessary to start developing the high-fi prototype quickly. The development of the hi-fi prototype is explained in chapter 4 Development.

### 3.2.5 Evaluate Design Against Requirements

Because of the Corona situation at the time in Norway, we did not think we could conduct any user testing. Finding a location where we could run our user testing, ensuring infection control, and recruiting participants could prove difficult, so we needed to plan our test carefully. Our team and another master student got the opportunity to borrow a location in Grimstad 1<sup>st</sup> of May. This gave us five days to plan our usability test. We did not have the time to report our research project to *Norsk senter for forskningsdata* (NSD), hence personal data was neither collected nor stored. In the end, five healthy participants were recruited and underwent testing. Although we would have preferred to have a larger group of participants, a small group of users is often enough in usability studies [83, p. 267].

### Test Participants

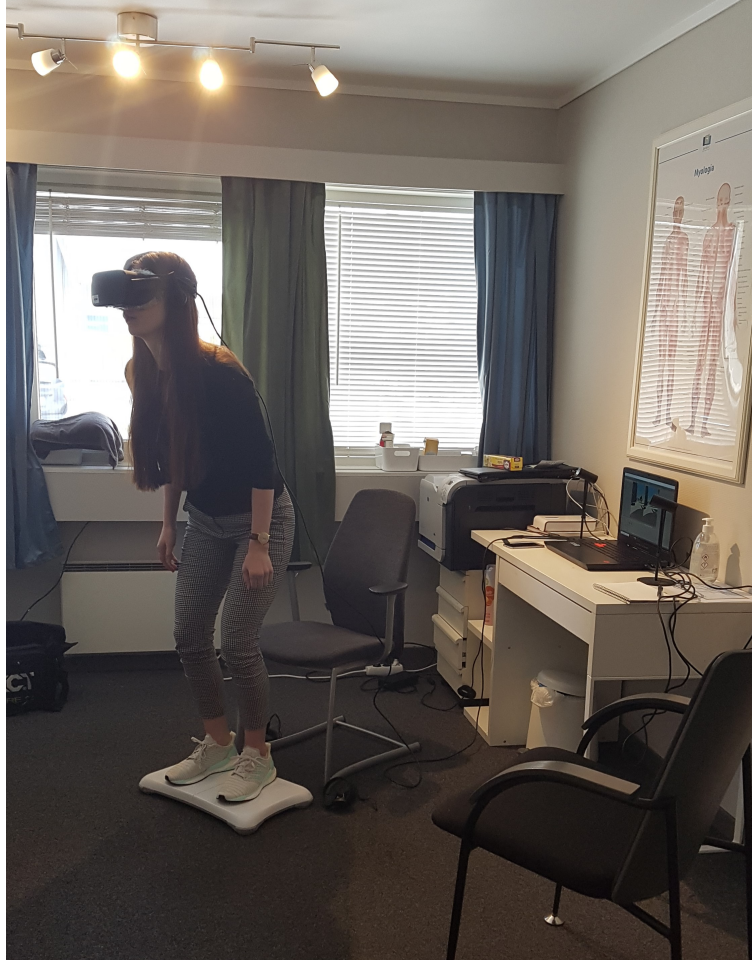
Four men and one woman participated in the usability testing, between the ages of 30 and 50. Most of the participants are technologically competent. Four of the participants had used VR and played video games before.

### **Aims of the User Testing**

The aim of the user test was to find out if a home-based rehabilitation system using the Nintendo Wii Balance Board and Oculus VR head-mounted display could be used for rehabilitation outside rehabilitation facilities. We wanted to specifically find out if using the system triggered cybersickness, and if the balance board could be a useful way of navigating around in the VR environment.

### **Home Environment**

Thanks to a fellow master student, we got access to a rehabilitation facility, who also tested his AR application that day. The facility is a privately owned health treatment center located in central Grimstad, where two of the rooms functioned as two separate test facilities. The two different projects were set up in their separate rooms, and underwent testing, sharing the participants that attended. Testing together allowed for a small pilot test of the set up before the actual test participants showed up. The fellow master student acted as a participant in our pilot usability test, and one from our team underwent pilot testing in his project. A pilot study is a small test run of a study you are about to conduct [76, p. 225]. Pilot testing is useful for discovering potential issues and setbacks that could cause the usability test to fail. Problems with technology, computer errors, or issues with the questions in the interviews are examples of practical issues that could come to light. We quickly discovered that we had some technical problems with the Wii Balance Board; it would not connect to the computer. The issue was resolved before the main tests commenced by merely changing the batteries.



**Figure 3.7:** The home-based prototype setup for user testing.

### Data Collection

Before the preliminary interview, all participants were informed of what the user test would involve, how it would be conducted, and of their anonymity. We created a document that we read out loud to each participant to ensure that they all had the same information.

We designed two semi-structured interviews which would be carried out before and after observational testing. The interview was conducted conversationally with one respondent at a time. We employed a blend of closed-ended and open-ended questions, thus allowing us to get the personal opinions of the respondent, get inspiration and new design ideas as well as semi-quantifying the overall impression of the VR solution. We also utilized the *Simulator Sickness Questionnaire* to ascertain whether the participants experienced symptoms of cybersickness. Seeing that we could not record the user test, the interviews and questionnaires were delivered verbally, and both interviewers took notes.

For the observational testing, the participants first got instructions on how to utilize the Wii Balance Board to control the character. For safety and the comfort of the participants, they

first tried to navigate the environment with the straight path while seated. Once they felt in control and safe, they were instructed to stand up and navigate to the end of the path. When this task was concluded, they went on to the environment with the branching path, where they would be observed and timed. During the observations, the participant was encouraged to keep talking about their experience, and we noted every instance where the participant either lost balance or stepped off the balance board.

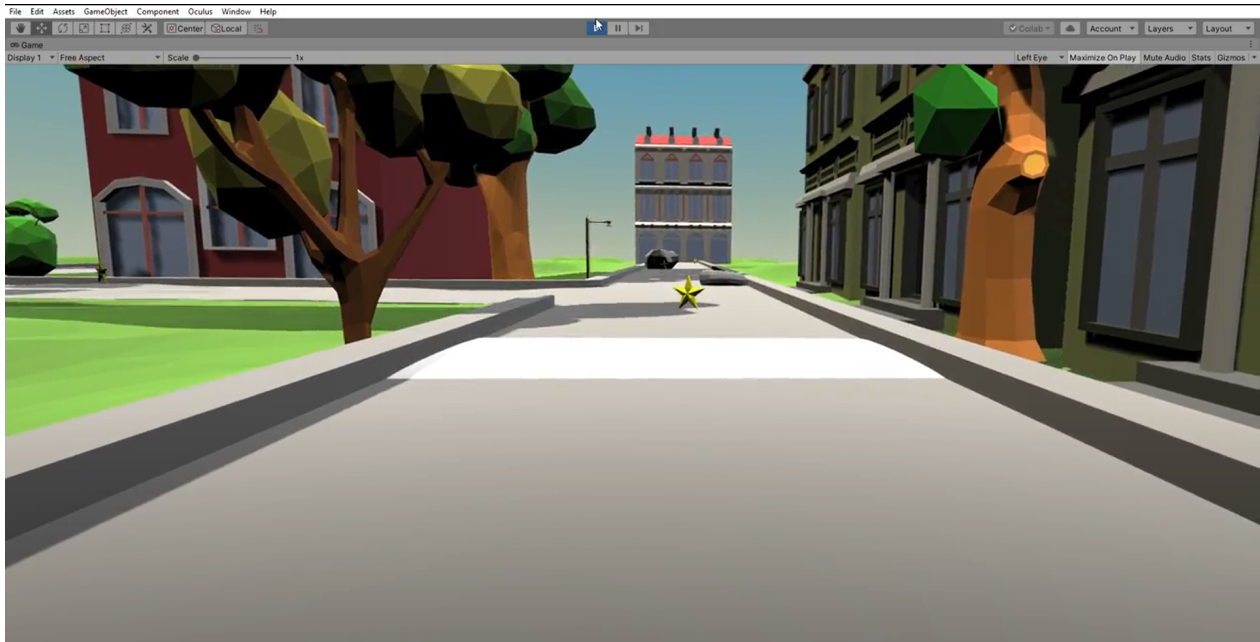
### **Simulator Sickness Questionnaire**

To discover if the participants experienced any symptoms of cybersickness after the usability test, we employed the Simulator Sickness Questionnaire (SSQ) [84]. This is arguably one of the most common questionnaires when investigating motion sickness, and it is also used for cybersickness. The questionnaire consists of sixteen questions describing different types of symptoms related to motion sickness, such as nausea, headaches, and fatigue, among other things. The answers are scaled from zero to three, where zero is no symptoms, and three are severe symptoms. SSQ's are taken before the usability test to determine the participants current state of health and retaken after to see if there are any changes in the participants state of health. The questionnaire was verbally conducted before and after the participant had tested the VR solution.

### **High-Fidelity Prototype**

For the user test, we created a branching path that the participant navigated along. The development of the path and VR environment will be further discussed in chapter 4 Development. Six stars were placed along the path that the participant had to capture. We placed stars on the path to ensure that the participants went where we wanted them to go. The placement of the stars also required the participants to do a 180-degree turn in one end of the path. We wanted them to do a 180-degree turn to determine if the WBB was fit for navigating in 3D space, if it would make them lose their balance or trigger cybersickness symptoms. The participant had to steer a character directly into the star, which, when caught, triggered audio to play so that the user could be sure that it was caught without having to turn around. The high-fidelity prototype was tested using the Oculus Rift and not the Oculus Quest, which was the initial plan. The reason is that the Oculus Quest can not receive Bluetooth data from the Wii Balance Board, hence it needs a cable to a computer instead of running the VR in the built-in system in Quest. Using the Quest with a cable is still in beta, and required some configuration. Choice of VR headset is further explained in 3.3.1 Head-mounted Display. It was determined that our time would be better spent on designing the user test, rather than integrating the Quest. Configuration of the Quest would be prioritized for the integration with the biomechatronics lab at UiA. As the user test was planned and accomplished within a week, the focus of the test was on the usability of the technical

tools, and if the participants would experience cybersickness. Hence, the development of game mechanics and game elements for this prototype was kept to a minimum.



**Figure 3.8:** The environment with branching path in VR utilized for user testing of the home system.

### Safety Measures

National measures put in place by the Norwegian authorities to deal with the Coronavirus pandemic required us to pay special attention to ensure infection control. Applying disinfectant on all surfaces between each participant, making sure to keep the 1-meter distance from each other at all times, and making sure that participants did not come to the facility simultaneously were some of the measures taken to ensure infection control. One discernible potential source of infection was the Oculus Rift, as it is worn on the face. The foam padding of the Oculus Rift, which touches the face, can be detached, making it possible to fit that part with cling film. The cling film was changed between each participant, and the device was cleaned with disinfectant.





**Figure 3.9:** Oculus Rift with cling film.

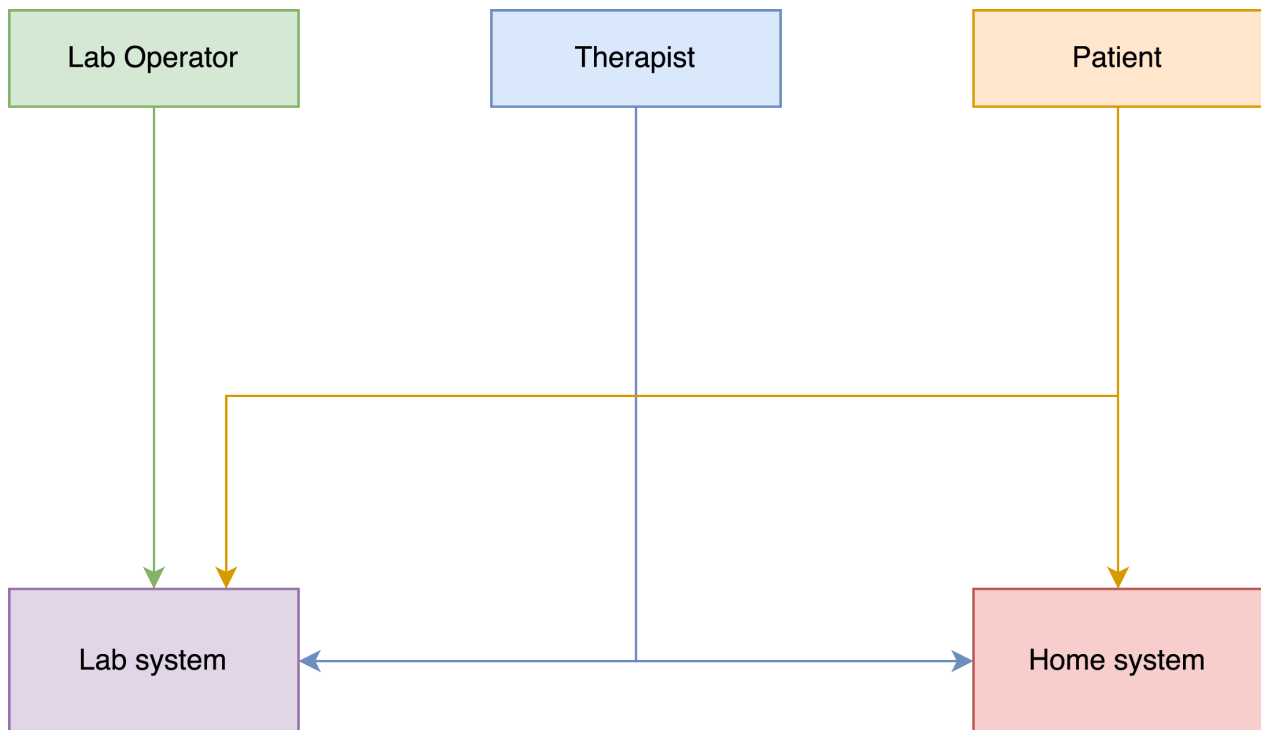
### 3.3 Technology

#### 3.3.1 Head-Mounted Display

As mentioned in chapter 2.6 Technical Aspects of VRR, UiA has three different HMDs that we could use. The HTC Vive met most of the standards suggested by Kourtesis et al. [57], but it required external sensors to be attached to the ceiling around the biomechatronics lab. This would prove difficult as the location of the biomechatronics lab is in a machine hall, where the ceiling is two floors up. Furthermore, the sensors are already attached to the ceiling in another lab at the University. The Oculus Rift also requires external sensors to be placed near the play area. The motion platform is rather high up and moves up and down approximately 1 meter, which would result in inaccurate tracking. Thus, the Oculus Quest was chosen as the optimal device, considering the alternatives and our situation. The Quest did not have the optimal refresh rate nor the appropriate field of view, but it requires no external sensors and can be developed to be utilized wirelessly. Although our initial plan was to utilize the Quest wirelessly, it could not be implemented with the University lockdown. The biomechatronics lab and VR solution will be further discussed in the coming chapters. Using the Quest wirelessly in the biomechatronics lab will be discussed in chapter 6 Conclusion and Future Work.

### 3.3.2 Systems Overview

This project started as a collaboration of a multi-disciplinary team to establish a biomechanics laboratory at UiA. After the national shutdown, the project had to evolve in another direction, focusing on home-based VR rehabilitation. Figure 3.10 describes the high-level system of the two systems that have been partially developed and investigated. Both systems will always involve a patient and therapist. The therapist must set up and explain the home-based system and be involved with the exercises in the biomechanics lab. In the biomechanics lab, authorized personnel is needed to operate the system, which in this case, is employees at the Norwegian Motion Laboratory. Figure 3.11 explains the devices which will form the biomechanics lab and the assumed inputs and outputs of the devices. Figure 3.12 explains the devices used in a home-based system and its inputs and outputs.



**Figure 3.10:** Overview of people directly connected to the biomechanics lab and the home system.

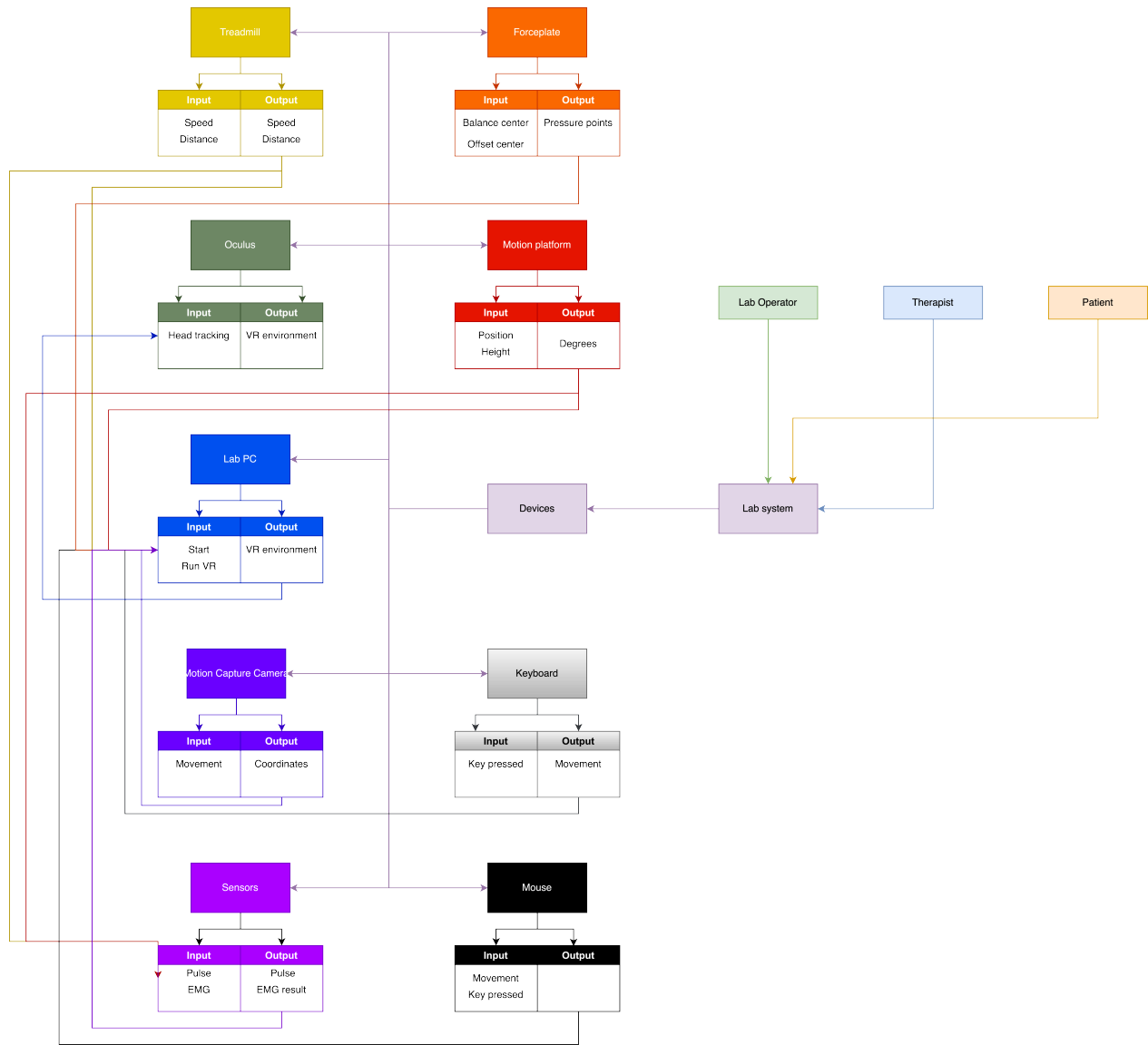


Figure 3.11: Overview of the lab system.

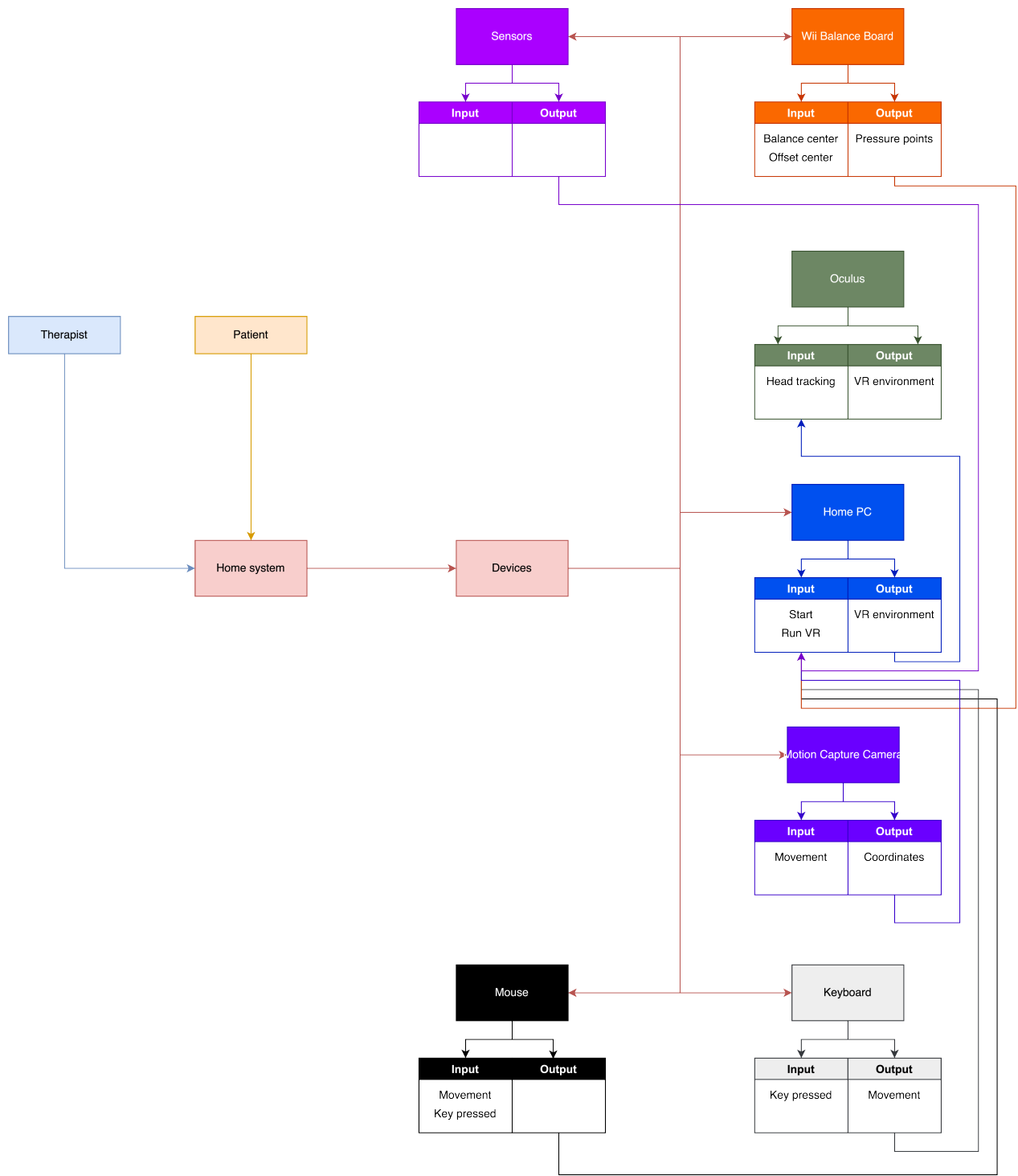


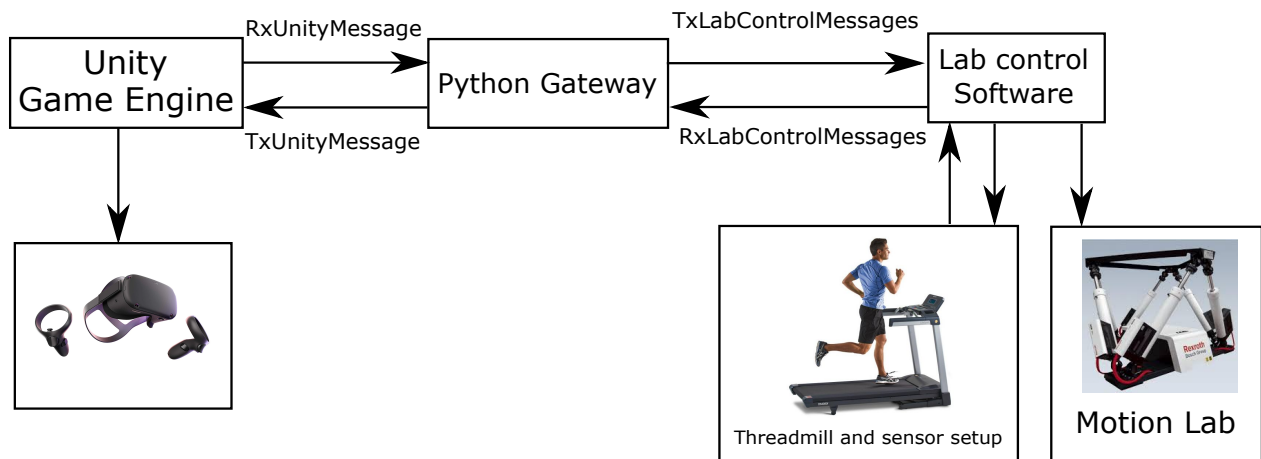
Figure 3.12: Overview of the home system.

## 4 Development

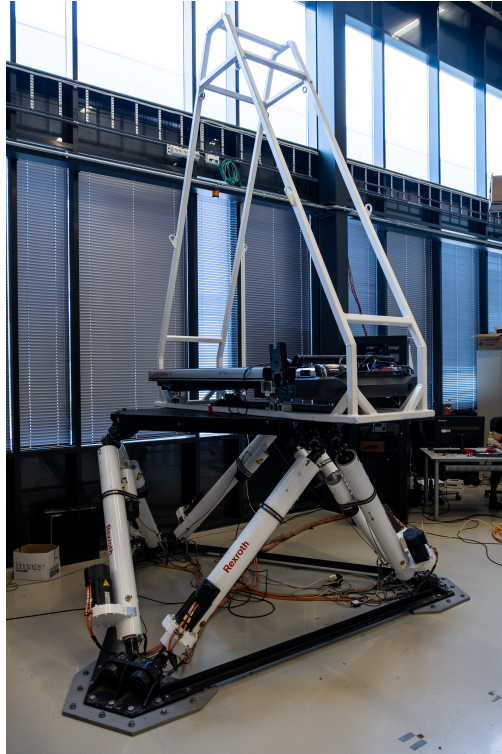
Our system has been developed using the Unity game engine [85], Blender [86] for 3D modelling and Microsoft Visual Studio Code 2019 [87] for code editing. A Python gateway program was developed to establish suitable middleware between Unity, the Norwegian Motion Laboratory, and eventually, the biomechanics lab. GitLab served as our software repository, and hence all developed software is found in our public Git repository [88]. Our team has some programming knowledge, but no experience in creating an internet gateway to communicate and convert application-level messages between Unity and the biomechanics control software. Thankfully, Dr. Sondre Sanden Tørdal had developed such a gateway and allowed UiA to use it.

### 4.1 Lab Setup

As explained in chapter 1 Introduction, the lab testing facility is situated in the Norwegian Motion Laboratory at the University of Agder, Campus Grimstad. The laboratory features two Stewart motion platforms capable of simulating real-time motion in all 6 degrees of freedom. For the biomechanics lab, a treadmill with an integrated force plate was placed on top of the smallest Stewart platform. Unity is utilized to create a VR environment, which will be displayed in a head-mounted display. Low-latency communication is needed between the various software and hardware components. Figure 4.1 illustrates the communication layout.



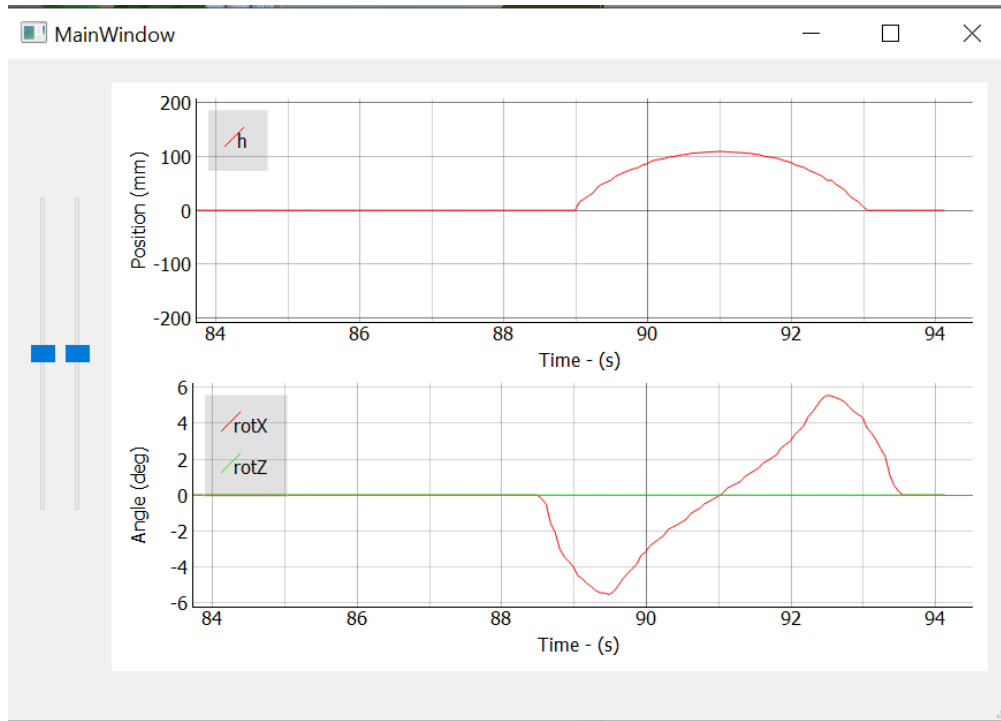
**Figure 4.1:** Communication layout used to facilitate lab testing.



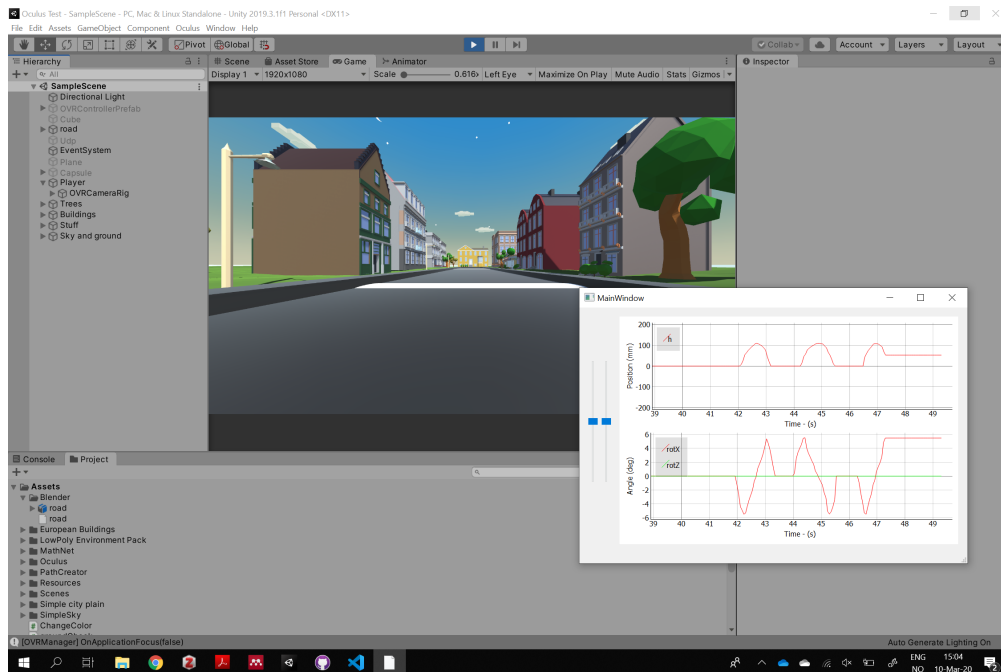
**Figure 4.2:** The biomechanics lab prototype.

## 4.2 Python Gateway

Unity is not prepared to control the Rexroth motion platform. Therefore a middleware was created using Python, a high-level programming language commonly used to serve as middleware in similar applications. The Python gateway program, hereby called the Python program, receives and transforms messages between the Unity application and the lab control software created by the mechatronics team. The Python program was also utilized during early integration testing directly with the Norwegian Motion Laboratory. This allowed us to see that the data sent from Unity is received as expected and can be used to control the motion platform. The Python program interface is rather simple, with two graphs representing the Unity characters movement in the  $y$ -direction ( $h$ ), inclination around the  $x$ -axis ( $\text{rot}X$ ), and inclination around the  $z$ -axis ( $\text{rot}Z$ ). It also has a timer that outputs the elapsed time and features two sliders, which was utilized during testing to verify that the Unity character could receive speed from the lab control software. The program was also used to verify that everything functioned correctly on our side before sending data to the lab control software or directly to the motion platform.



**Figure 4.3:** The Python program visually shows that the character has moved over a bump which is about 10cm tall with an inclination in x at about 6 degrees.



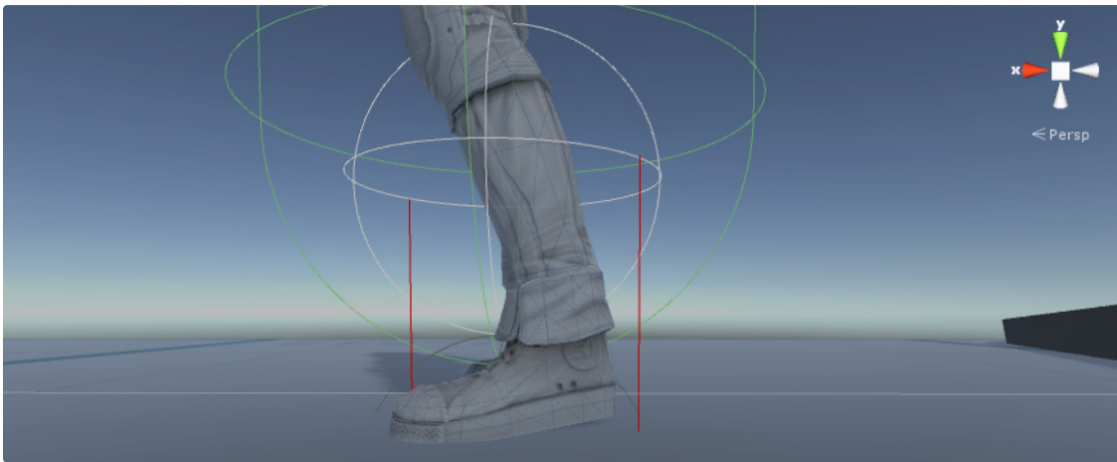
**Figure 4.4:** Game play in Unity and Python gateway outputting height and rotX of the character.

### 4.3 Raycasting

To be able to tie together our solution and the lab control system, we required that data was gathered from the Unity character in real-time and sent to the Python program. In several meetings with the mechatronics team and engineers working at The Norwegian Motion Laboratory, we determined three parameters that would provide the necessary data to control the motion platform; the terrain height at the current character position and the two rotation angles describing the terrain gradient under the character.

Our initial attempt at this was to utilize Unity's *Rigidbody* component on the character, which allows for acquiring physical data about the character using *transform*. Rigidbody is a component that will put objects (in this case, the character) motion under control of Unity's physics engine, and transform gives us some control of the physical location of the object, e.g. the degrees of a bump below the character. Though this proved somewhat successful, it did not provide data accurate enough to control the motion platform smoothly. We could not access the degrees of inclination between 0 (flat terrain) and  $n$  (max inclination). This would result in the platform being level with the ground one second, and go straight to the max inclination of the bump the next.

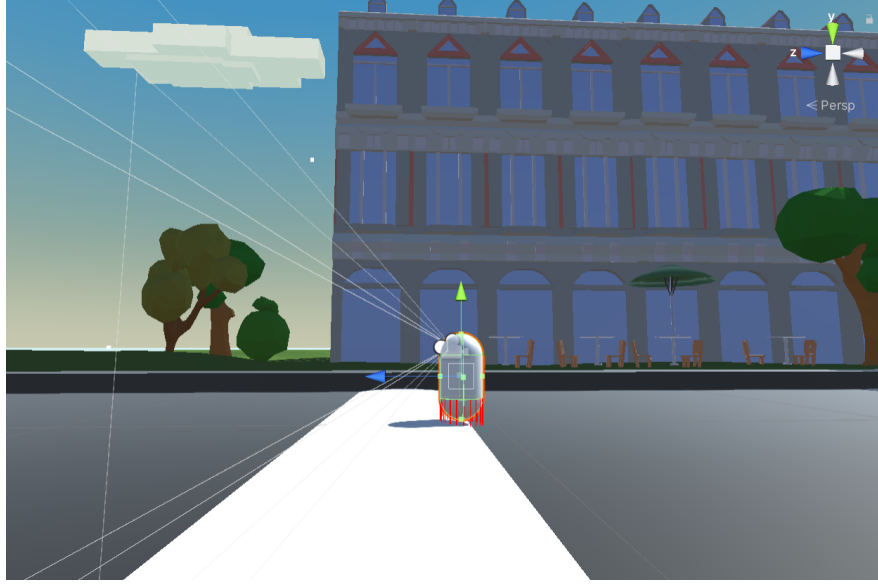
We figured that measurements of several points on the terrain below the character would provide us with accurate enough data to generate the desired movement of the motion platform. This idea is based on an article by Josh Winn [89] posted on The Hidden Signal. In the article, he finds the angle of a sloped ground below his character by using raycasting. In simple terms, a ray is cast from a specific point which, when colliding with an object, returns detailed information about the hit point. In this case, the distance between the character and the terrain.



**Figure 4.5:** SphereCast and two raycasts (red lines) as utilized in Josh Winn's solution [89].



After implementing this solution, it was clear that we were on the right track, but further accurate measurements were needed for safety and to get readings in all the directions that the character might move. Thus twenty raycasts were utilized to measure the terrain below the character.



**Figure 4.6:** The character going over a bump with visible raycasts.

#### 4.4 Terrain Observer

In the C# script called *TerrainObserver* all of the raycast hits are used to form a point cloud which again is used to estimate a plane representing the terrain found below the character. The points can be seen as the following data set:

$$\text{PointCloud} = \{p_1 \cdots p_n\} \quad (1)$$

The plane estimation can be realized using several methods, and most of them are based on linear or non-linear regression. The estimated plane is defined by the plane normal vector  $\vec{n}$  and hence the process of finding this normal vector is given as:

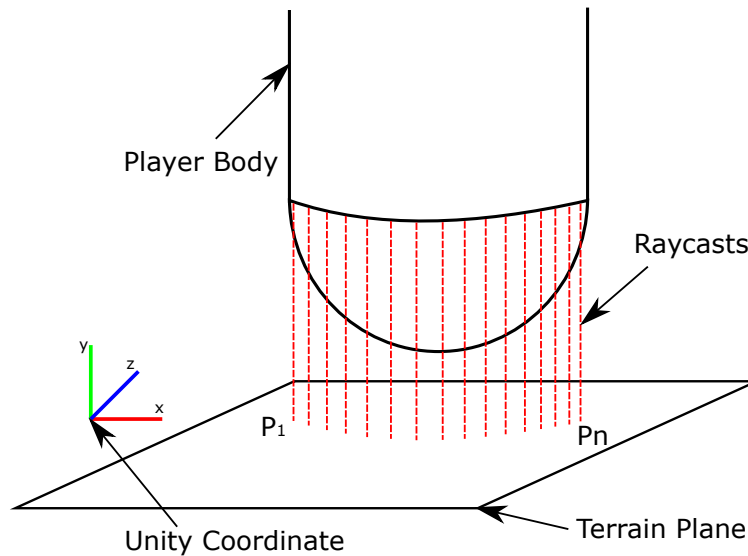
$$\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \text{RegressionProcess}(\text{PointCloud}) \quad (2)$$

The two angles representing the terrain inclination relative to the character is found from taking the inverse tangent to the resulting normal vector according to:

$$\text{RotX} = \text{atan2}(n_z, n_y) \quad (3)$$

$$\text{RotZ} = \text{atan2}(n_x, n_y) \quad (4)$$

where  $\text{atan2}$  is the inverse tangent function which is valid for angles ranging in between  $\pm 180$  degrees.



**Figure 4.7:** Raycasts on plane.

#### 4.4.1 Data Communications

User Datagram Protocol (UDP) is the communication protocol that is utilized in the communication between our solution and the lab software. UDP is a connectionless communication transport protocol that allows computer applications to send messages (datagrams) to other hosts using Internet Protocol (IP). UDP is often used for time-sensitive transmissions, which is necessary for this project as data needs to be sent and received quickly to prevent delays. However, using UDP opens up for dropping packets. The data which is sent and received is listed and explained below. A sequence number could be added to detect packet loss. In this solution, we did not integrate sequence numbers as we felt it was not necessary at the current state of the system.

The initialization and reset procedures of the motion platform are taken care of by the Mechatronics group. The initialization puts the platform to a state where the user can easily get up on the biomechatronics lab, and hence the system is engaged to run in a closed loop with our Unity solution. The reset procedure ensures that the system is again moved to the initial position and is again ready to be engaged to active mode when needed.

#### RxUnityMessages

RxUnityMessages is the data the Python program receives from Unity. It contains three parameters;  $h$  for the height of the Unity character on the terrain (i.e. the distance between the character and ground),  $\text{rotX}$  for the X-rotation angle of the character, and  $\text{rotZ}$ , which contains the Z-rotation angle of the character.

```
class RxUnityMessages(ctypes.Structure):
    _fields_ = [
        ('h', ctypes.c_float),        // Height of unity character
        ('rotX', ctypes.c_float),     // X-rotation angle of unity character
        ('rotZ', ctypes.c_float)     // Y-rotation angle of unity character
    ]
```

### **TxUnityMessages**

TxUnityMessages is the data that Unity receives from the Python program containing the speed that the Unity character should move. In the home-based solution, speed can be controlled by leaning on the WBB, or arrow keys on a PC keyboard. In the biomechatronics lab, this speed is received from the lab control software; "rotationSpeed" through the force plate and "forwardSpeed" is set in the lab control software.

```
class TxUnityMessages(ctypes.Structure):
    _fields_ = [
        ('forwardSpeed', ctypes.c_float),    //Forward speed of Unity character
        ('rotationSpeed', ctypes.c_float)    //Rotation speed of the Unity character
    ]
```

### **RxLabControlMessages**

RxLabControlMessages is the data the Python program receives from the motion platform or subsequently, the lab control system. This data is standardized and was provided by The Norwegian Motion Laboratory when communicating directly with the motion platform (appendix H). When communicating with the lab control software for the biomechatronics lab, the data was provided by the mechatronics team.

### **TxLabControlMessages**

TxLabControlMessages is the data the Python program sends to the motion platform or the lab control system. This data is standardized and was provided by The Norwegian Motion Laboratory (appendix G). The data was transformed from a left-hand coordinate (Unity standard) to a right-hand coordinate, which is what the motion platform utilizes.

## **4.5 Unity Project**

Unity is a cross-platform game engine used for developing video games for desktop platforms, consoles, mobile games, and web plugins. This project used Unity for the development of the VR environment, and Blender was used to create the path.

The first environment was intended for the first user tests and was used for initial communication testing between the VR solution and the biomechatronics lab. The second environment was used for user testing and in the communication integration in May.

Simple low-polygon game objects were found in Unity's Asset Store and placed around in the

scene to create the VR environment. A low-polygon style gives the environment a blocky and simple look. The reason for this choice of style over a more realistic one is simply because low-polygon 3D models are faster to render, which reduces the risk of lag. The style has a retro feel to it, reminiscent of games from Nintendo 64.

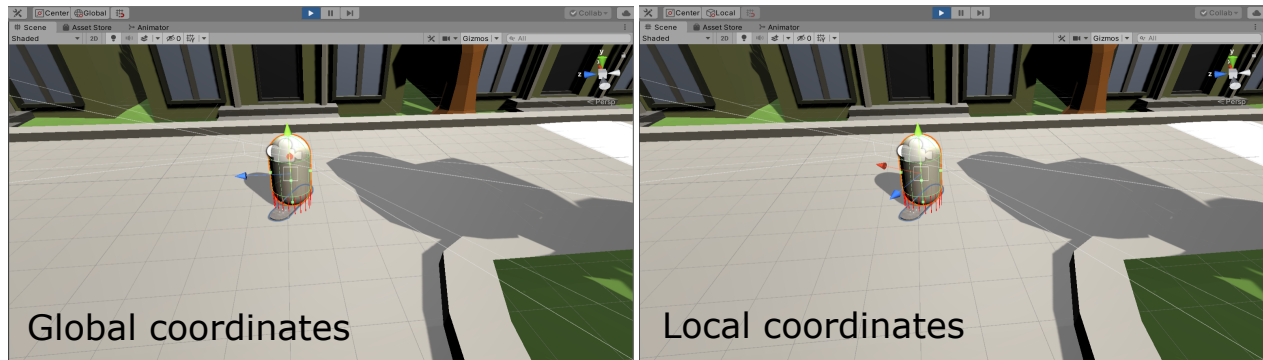


**Figure 4.8:** View of the user in VR of the first environment.



**Figure 4.9:** Overview of the second VR environment with forked path.

Movement and character code is written using C#. The character moves forward and backward, as well as to the sides. When moving to the side, it was important that the camera, which is what is displayed in the VR headset, moved in a way that would be natural when on a skateboard. We wanted the camera to be pointing in the characters local Z direction. To achieve this, the camera/character needed to rotate around the y-axis when the user shifted the weight on the force plate or Wii Balance Board to left or right. This resulted in a code where speed is applied to the local coordinate of the character (appendix I).



**Figure 4.10:** Images showing the global and local coordinate of the character.

## 4.6 Terrain Creation using Blender

Unity is an excellent game engine, but it is not the best tool for 3D modeling. In this project, we needed to create more advanced terrains, and hence Blender is used to create these models since it is easily integrated with Unity. The Blender file was placed directly into the Unity project and is automatically updated when changes are made in Blender. Two paths were created for the solution; one straight and a second path that branched off in two directions. With the second path the bumps moves the platform in all 6 degrees of freedom, whereas in the first the motion platform only moves up and down and in the pitch direction. A curb was added to make sure that the character could not go off the track and risk going over bumps that the motion platform and user could not handle.

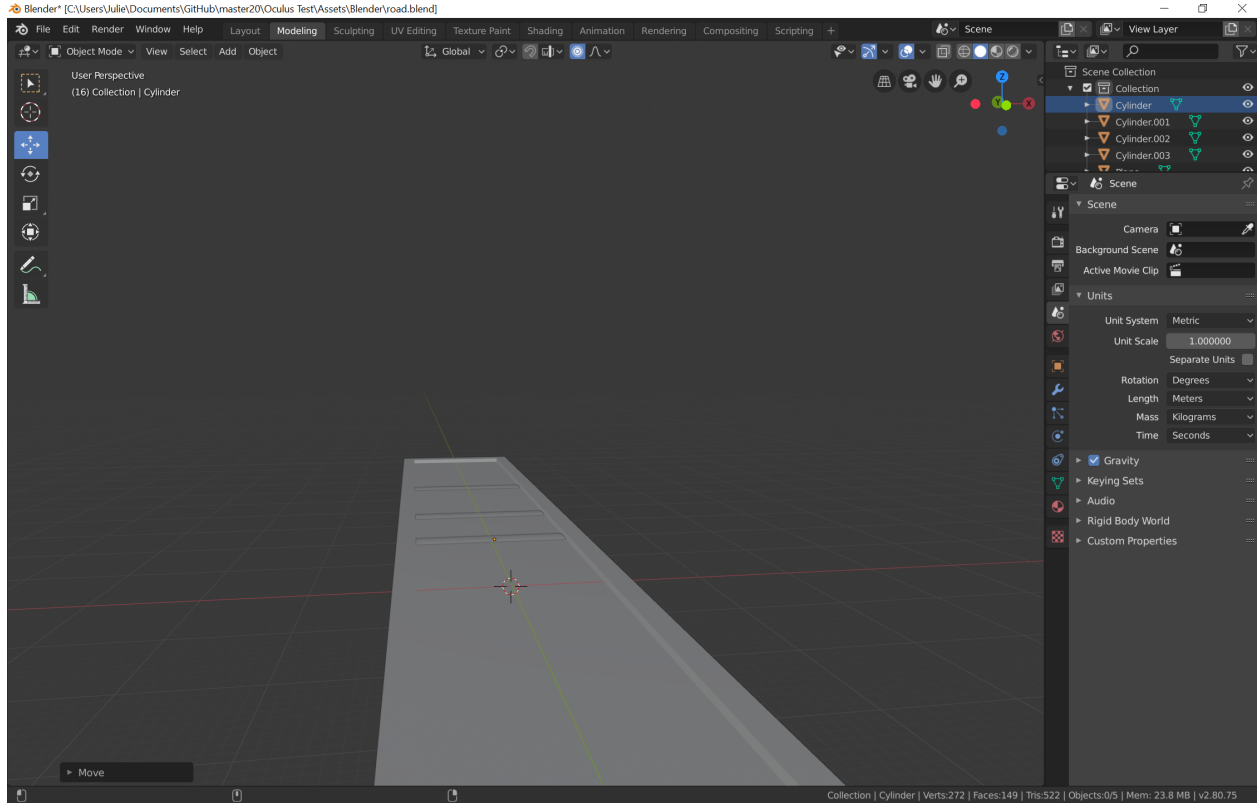


Figure 4.11: Screenshot of the first path created in Blender.

## 4.7 Wii Balance Board

In consultations with the mechatronics team, we were encouraged to use a joystick to control the Unity character. This was because the biomechanics lab would have integrated sensors in the treadmill, which could be used for moving around in VR by leaning and acquiring data on the users balance. The sensors would be quite similar to what is utilized in a Nintendo Wii Balance Board (WBB), which was available to borrow from the University.

To be able to use the WBB to control the character, we had to download a program called WiiBalanceWalker [90]. This program allowed us to use the board as the keys W, S, A, and D, and thus moving the player forward, backward and to the sides, respectively. This posed some issues as we would instead use the WBB as a joystick to get more control of movement and speed. After some testing, we found that using the Wii board with keyboard inputs worked well enough for testing before setting it up to work with the force plate integrated treadmill. The WBB was also utilized in the user testing of the home-based solution.

## 4.8 System Integration Tests of the Biomechanics Lab

Two communication tests were carried out in the Norwegian Motion Laboratory during the semester. One a few days before the University's lock-down in March and one right after the

University allowed critical student projects to enter at the end of April.

In the middle of March, we had developed the prototype of the VR solution, complete with the possibility of communicating directly with the Motion Lab. The communication was tested and proven successful on March 10<sup>th</sup>. Following our plan for the master project, we were supposed to integrate our solution with the mechatronics team solution in the middle of March and thus commence user testing. Due to the lock-down, this could not be achieved according to the plan.

By the end of April, the University allowed a small number of people to enter. This allowed us to test our solution to make sure it was ready for integration with the biomechanics lab and to gather video footage of the functioning solution. In case the biomechanics lab was not up and running before the end of the project, the footage would show that our solution worked.

By the first week in May, the biomechanics lab was ready. Our two teams integrated the two solutions on May 8<sup>th</sup>, resulting in a functioning biomechanics lab with VR. See themvideo from the lab at Youtube: <https://youtu.be/wM65kRQNrtI>. With the limited time to work on their solution, the mechatronics team has not yet integrated the treadmill on the biomechanics lab. Nonetheless, our solution is ready to receive data that can affect the characters speed using a treadmill.



**Figure 4.12:** The biomechanics lab with user.

## 5 Findings and Results

In this chapter, we will present and discuss the results from the user tests conducted on May 1st, which consisted of two interviews, two Simulator Sickness Questionnaires, and observation. The result from the second interview is presented in graphs to give a better overview of our findings.

### 5.1 Findings from Observation

During testing, the participants were all asked to use the Think Aloud method, which is described in chapter 3.1.3 Testing and Evaluation methods. The downside of using this method was that the participants sometimes forgot to voice their thoughts. There could be several reasons for this: The participants were focused on the task of collecting the stars. It could also be that they were uncomfortable with voicing their thoughts aloud, or perhaps they were too focused on the Wii Balance Board (WBB) not being sensitive enough. Three out of five participants experienced balance issues a few times. Several things could cause balance loss, but we observed that it most commonly happened when they did the 180-degree turn. The most natural assumption as to why this happened is that the use of a VR HMD coupled with having to use their balance to steer on the WBB created difficulties. Considering that the WBB sensitivity is not very substantial, the participants leaned over too much to compensate for the lack of sensitivity and therefore lost their balance. We could also hypothesize that it could be because it was their first time using such a system. Perhaps if the participants used the system over time, we would see less balance loss. Although almost all of the participants felt safe while using the home-based system, we can not assume that applies to patients. For patients to use the current home-based prototype, the WBB must be configured better, or new technology should be considered, and instead of a head-mounted display, a large screen could be used.

### 5.2 Results from Post-Interview

After the participants had tried the home-based VR solution, they were presented with seven questionnaire items about their experience. Five of the questionnaire items were closed-ended statements, and two were open-ended questions. We dubbed the VR solution "SkateBalance" for the occasion.

#### **Questionnaire Items from Post-Interview:**

**Q1:** Using "SkateBalance" is a frustrating experience

**Q2:** "SkateBalance" is easy to use

**Q3:** Navigating with the help of Wii Balance Board is easy



**Q4:** I feel safe while using "SkateBalance"

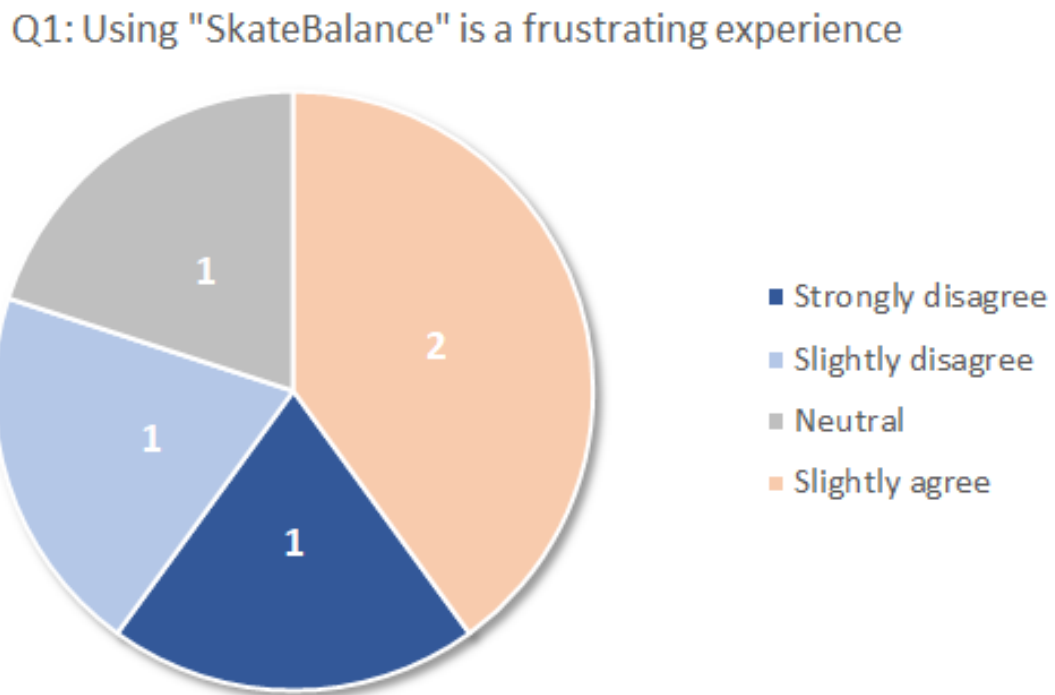
**Q5:** The use of VR in "SkateBalance" gave me discomfort

**Q6:** How was your experience using VR and Wii Balance Board in this Way?

**Q7:** Do you have any suggestions for changes that can make the experience better?

### 5.2.1 Questionnaire

The five closed-ended question were phrased like a statement and the participants answered them on Likert scale from one ("strongly disagree") to seven ("strongly agree").

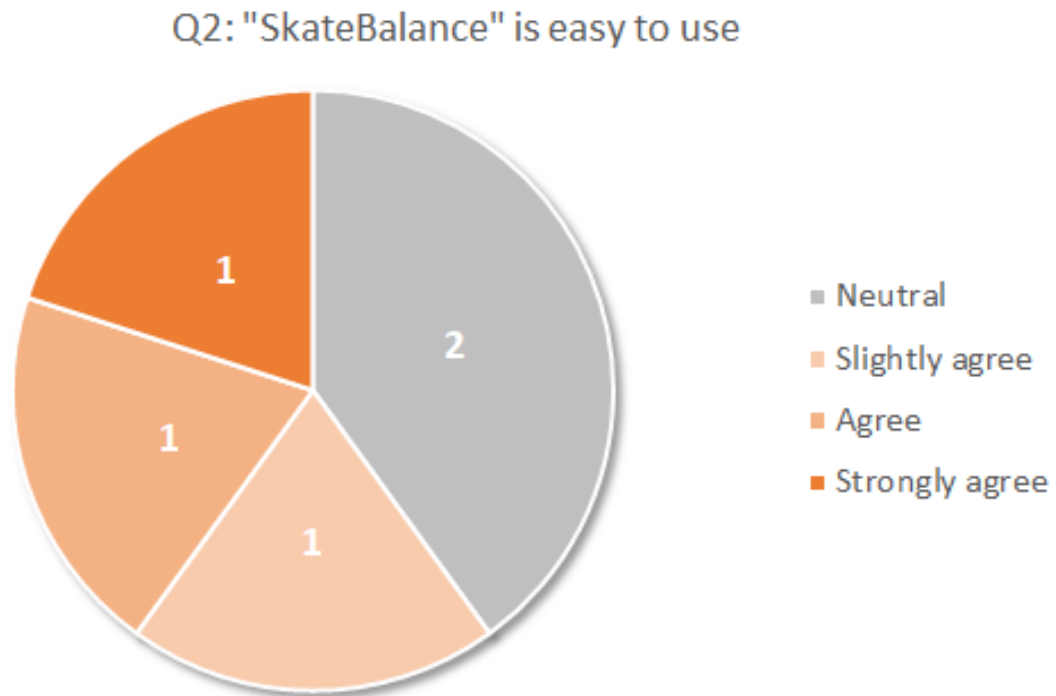


**Figure 5.1:** Q1: Using "SkateBalance" is a frustrating experience.

The result from Q1 are displayed in figure 5.1. Participant 1 (P1) and participant 3 (P3) found the experience of using "SkateBalance" slightly frustrating. P1 remarked in the open-ended questions that he felt like he had to turn his whole body to turn the character around and that the lenses in the VR headset got foggy because of condensation. P3 said in the open-ended questions that the WBB was a bit frustrating to use, the correspondence between movements was not always correct. In question 3, P3 answered neutrally to whether the WBB was easy to navigate with. P3 also experiences some symptoms of cybersickness. The three remaining participants either found the experience non-frustrating or neutral.

The results from Q1, shows that using "SkateBalance" is for some a frustrating experience.

This might be attributed to the WBB lack of sensitivity, the fact that it was the first time the participants tried such a system, or from other issues such as condensation or cybersickness. It could also be attributed to technical factors; the WBB has to be calibrated to each individual. P1 and P3 might not have stood correctly on the board during calibration or moved after it was calibrated. This could have resulted in a frustrating experience, as this would make it somewhat difficult to navigate properly.



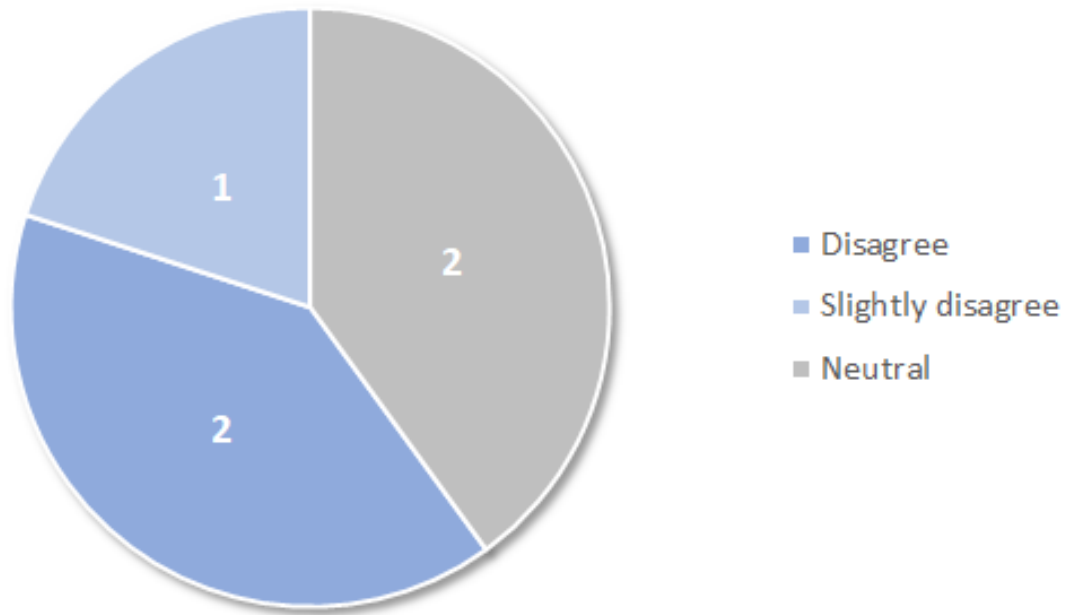
**Figure 5.2:** Q2: "SkateBalance" is easy to use.

The result from Q2, displayed in figure 5.2, gives some answers to the question of usability. The participants spent between 1 minute and 30 seconds to 3 minutes and 4 seconds on collecting all the stars. This indicates that "SkateBalance" could be easy to learn, effective, and efficient. Overall the participants more or less found the whole experience of using "SkateBalance" as easy. Participant 5 (P5) mentioned in question 6 that the task itself was easy, but the path was difficult to navigate, which explains why he answered "neutral" on this question. P3 agreed that "SkateBalance" was easy to use and said that she could see the value "SkateBalance" would bring to physical therapy.

From the answers to this question and Q1 we can hypothesize that "SkateBalance" is easy to use and understand, but that the WBB should perhaps be changed out for a more sensitive device or researched further. Non-functional requirement 14 states that people with little

to no training shall use the product. From the answers to Q2, the prototype was easy to learn and use. Non-functional requirement 17 states that the product shall be easy to use by people between the ages of 13 and 80+. Considering that our user test involved a small sample size of people between the ages of 30-50, the results might indicate that the prototype may be usable for that age group.

### Q3: Navigating with the help of Wii Balance Board is easy

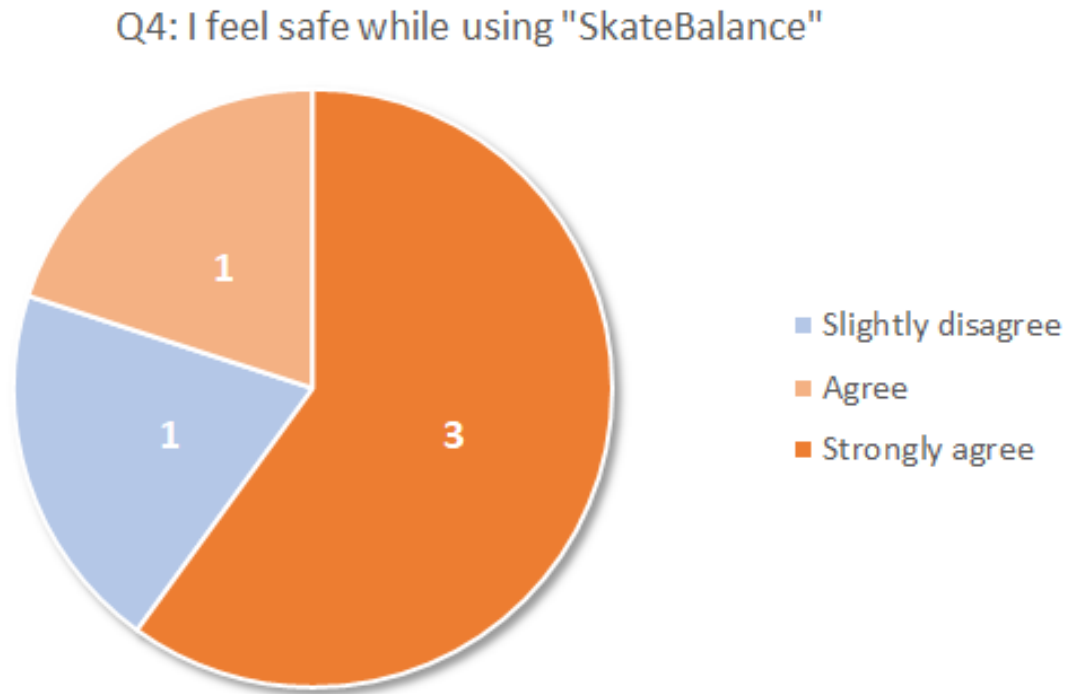


**Figure 5.3:** Q3: Navigating with the help of Wii Balance Board is easy.

In the study by Borghese et al. [27], they found that the use of the WBB in a home-based rehabilitation environment was deemed usable. They only used the WBB for movement in one mini-game to move the character laterally, not in 3D space. They also used the WBB for gathering patient data. As stated by most of the participants in our user test, the WBB was not sensitive enough to control the character adequately. With further investigation, we could perhaps increase the sensitivity of the WBB and get a different result on the next potential usability test. One should also consider that the WBB is quite old and perhaps better suited for other purposes such as data gathering or for other systems where character movement is not in a 3D world.

The non-functional requirement number 11 states that the solution, called *product* in the requirements, shall be easy for the user to navigate. In terms of navigating the character in the VR environment, this user test showed that the prototype was not easy to navigate.

During the observation, we could see that most of the participants struggled with rotating 180 degrees without crashing into the curb. This further demonstrates that the WBB might not be the best tool for a home-based rehabilitation program. Although, it would be interesting to test further the usability of the WBB in relation to rehabilitation outcomes.

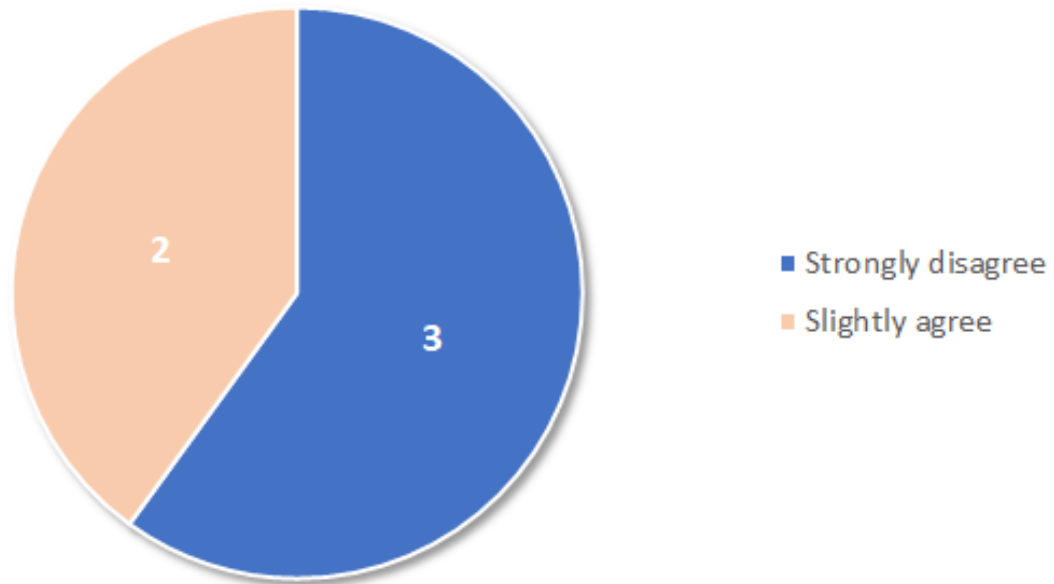


**Figure 5.4:** Q4: I feel safe while using "SkateBalance".

As mentioned in chapter 2.6 Technical aspect of VRR, the use of HMDs with WBB in a home-base rehabilitation environment might cause safety issues. The result displayed in figure 5.4 shows that four out of five participants felt safe while using the HMD. None of the participants fell or stepped off the WBB during the usability testing, but three out of five lost their balance a few times. Participant 2 (P2) answered that he felt slightly unsafe and explained in the open-ended question that he would have liked to have something to hold on to.

Non-functional requirement 12 states that the user should feel safe when using the product. The results from Q4 show that overall the participants felt safe. The reason for P2 feeling unsafe might be attributed to cybersickness, specifically dizziness, with eyes closed. The prototype was not tested on the intended user group, who might have issues with balance and standing. Five healthy adults were tested, and although they found the system overall safe, we cannot safely say that our system is safe for the intended users from this result.

### Q5: The use of VR in "SkateBalance" gave me discomfort



**Figure 5.5:** Q5: The use of VR in "SkateBalance" gave me discomfort.

Figure 5.5 show that two out of five participants felt discomfort using VR in "SkateBalance". These two participants were P2 and P3, who also showed mild cybersickness symptoms, as presented in table 5.1. This result answers research question 2, which will be discussed in 5.5 Main Contribution. It also support research theories on cybersickness, which is explained further in chapter 5.3 Results from the Simulator Sickness Questionnaire.

In the sixth question, we asked the participants: "How was your experience of using VR and Wii Balance Board in this way?"

P1 said he kept turning his whole body to turn the character around, and he thought it was because the WBB was not sensitive enough. He found the WBB somewhat difficult to use. He liked the overall look of the VR environment.

P2 also said he found the WBB difficult to use when navigating; the character's speed was uneven, and he thought the turn of the path was a bit abrupt. Participant 2 also felt some symptoms of cybersickness, which made him a bit dizzy. This made him feel a bit unsafe. He found it easy to understand how to navigate and use the solution, and it was fun to use.

P3 found the overall experience positive and fun but found the WBB a bit frustrating to use because it was difficult to control the character. There was not always a correspondence

between different pressures. She said she felt like she used muscles in her legs, and that this was positive.

P4 found the experience exciting, as he had never tried such a solution before. He found the overall experience good and fun. He would like the character to move faster, but follows up with "though this might make it harder". He did not think that he was doing an exercise/physiotherapy when immersed in the environment. He also thought it could be useful for balance, but said that he found it a bit difficult to navigate with the WBB.

P5 found the experience fun. He thought that the WBB was not sensitive enough; it felt digital and lacked gradual speed. The task itself was easy, but the path was difficult. He found turning around difficult and said it should be possible to turn around on the spot. Navigation seems a bit out of sync, as sometimes the WBB responded slowly. He also said that he had tried a VR roller coaster experience created at UiA where he got cybersickness almost immediately. He felt no symptoms in this solution, which he was very happy about. He also felt more in control of this solution.

In the seventh question, we asked the participants: "Do you have any suggestions for changes that can make the experience better?"

P1 said that the WBB should be more sensitive. He also had difficulties with condensation on the glasses because of the plastic that was wrapped around the foam padding.

P2 suggested that an overall "smoother" user experience would improve the solution; this was in relation to navigating with the WBB. He also suggested that it could be a good idea to provide potential users with something to hold on to if they feel dizzy. Adding background music, and the sound of a skateboard rolling would also improve the solution. He suggested that the rolling sound could work well to indicate that you are indeed moving.

P3 would like to see improvement on the navigation in the game using WBB, and she thought the turning radius was too big (when applying pressure to one side to turn around or turn in a turn in the path).

P4 suggested that the speed should increase if leaning forward a lot, as this would be useful on the long stretches of road.

P5 also mentions that navigation should be easier. It needs more sensitivity and correlation between movements. Also, the sessions in VR should be short because the heat of the VR headset makes you very warm.

### 5.3 Results from Simulator Sickness Questionnaire

The participants were all asked to answer a Simulator Sickness Questionnaire (SSQ) before and after testing the VR solution. The answer alternatives are given on a scale of zero ("not at all") to three ("severe"), in relation to how much a given symptom is affecting the participant.

Question	Pre					Post				
	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
General discomfort	0	0	0	0	0	0	1	1	0	0
Fatigue	0	0	0	0	1	0	0	0	0	1
Headache	0	0	0	0	0	0	1	0	0	0
Eyestrain	0	0	0	0	1	0	1	1	0	1
Difficulty focusing	0	0	0	0	0	0	1	0	0	0
Increased salivation	0	0	0	0	1	0	0	0	0	0
Sweating	0	0	0	0	1	0	0	1	0	1
Nausea	0	0	0	0	0	0	1	1	0	0
Difficulty concentrating	0	0	0	0	1	0	1	0	0	1
Fullness of head	0	0	0	0	0	0	1	0	0	0
Blurred vision	0	0	0	0	1	0	0	0	0	0
Dizziness (eyes open)	0	0	0	0	0	0	0	0	0	0
Dizziness (eyes closed)	0	0	0	0	0	0	1	0	0	0
Vertigo*	0	0	0	0	0	0	0	0	0	0
Stomach awareness**	0	0	0	0	2	0	0	0	0	2
Burping	0	0	0	0	0	0	0	0	0	0

\*Vertigo is experienced as loss of orientation with respect to vertical up-right  
\*\*Stomach awareness is usually used to indicate a feeling of discomfort that is just short of nausea

**Table 5.1:** Pre and Post SSQ score.

Figure 5.1 shows that participants 1, 2, 3, and 4 registered no symptoms before the usability test. P5 registered mild in six of the symptoms and moderate in one. After the test, P1 and P4 experienced no change in symptoms, P2 and P3 experiences mild changes in some of the symptoms, and P5 experienced loss of symptoms, possibly related to the fact that he had just eaten before answering the preliminary SSQ. In the pre-questionnaire, he had mild blurred vision, which in the post-questionnaire had disappeared. We postulate that he forgot what he had answered in the pre-questionnaire. The participants who experienced mild symptoms were the youngest of the test participants, both in their early thirties. According to LaViola

[46] and David et al. [47], younger people are more susceptible to cybersickness. Our sample size was too small and limited to verify this, a larger sample size is required to confirm the theory but the result might indicate that age was the reason for the experienced symptoms.

Although this user test had a small sample size, it supports previous research claims [46], [47] that age is a contributing factor to cybersickness. Younger people are more susceptible to cybersickness.

## 5.4 Findings from Integration with the Biomechatronics Lab

On May 8<sup>th</sup>, the VR solution was integrated with the biomechatronics lab. Five people related to the project tested the biomechatronics lab with the VR solution. These tests brought to light some new findings and further work. One person from our team has tested both the home-based solution and the biomechatronics lab and found that the force plate utilized in the biomechatronics lab was significantly more sensitive than the WBB. This allowed for a more natural skateboard experience. This was the overall impression of everyone who tested the biomechatronics lab. One person remarked that it would be nice if the character had legs, as it was a bit disorienting looking down without seeing legs.

In the home-based solution, the participants in the user test spent a maximum of 3 minutes in VR. The people who tested the biomechatronics lab spent considerable more time in VR, where one used it approximately 15 minutes continuously, which is recommended as maximum time by research [49]. None of the people who tested the biomechatronics lab experienced cybersickness. Although the sample size is quite small, we theorize that the movement felt more natural with the motion platform and sensitivity of the force plate, which led to no conflict between the visual and vestibular senses.

The biomechatronics lab, as it is presented today, is not necessarily suited for user testing on patients but is ready for user testing and research with healthy individuals. The biomechatronics lab might look daunting at first glance, as it is quite big and only reachable by ladder. A steel frame was created and placed on the platform where users are attached with a harness to the frame for safety. Everyone who tried the biomechatronics lab that day found the experience to be enjoyable and fun, which is promising. One of the testers even mentioned that he was so immersed that he forgot how high up he was on the platform. The creation of the biomechatronics lab at the university is in its early stages and will be further developed and researched in the coming years.



## 5.5 Main Contributions

### **RQ1: How to design a VR-based solution for a biomechatronics rehabilitation lab?**

The primary goal of this project was to create a VR environment for a biomechatronics lab. We developed a VR environment, and a team of mechatronic students created the biomechatronics lab. At the end of the project period, the two systems were integrated, thus creating a functioning biomechatronics lab. To develop the VR solution, we followed a Human-Centred Design approach. The VR solution was designed and developed with a 3D software, game engine, and developer tool.

### **RQ2: Will VR elicit negative side-effects on patients?**

The home-based solution was tested on five healthy participants between the ages of 30 and 50. The participants had to answer eight questions and an SSQ before testing "SkateBalance". After testing, they had to retake the SSQ and answer seven questions about their experience. The questions showed that two of the participants experienced mild symptoms of cybersickness. In the systems integration test, we found that the people who tested the biomechatronics lab did not experience any symptoms of cybersickness. We theorize that this was because both the visual and vestibular senses were stimulated from the motion platform and VR environment, which supports *The Sensory Conflict Theory*. However, this cannot be fully verified without conducting SSQs on both solutions, and without a bigger sample size of test participants.

User tests of the home-based solution indicate that using a VR headset in such a system can cause an imbalance, which can result in falls. None of the participants fell or stepped off the WBB in our user test, but they are healthy individuals and not patients who might have poorer balance because of neurological conditions. As suggested by one of the participants, something to hold on to or displaying the VR on a screen could make users safer.

In the biomechatronics lab, a harness secures the user to a steel frame on the platform. Although the user is safe on the platform, the biomechatronics lab in its current state can look intimidating. This might result in the feeling of being unsafe, even if that is not the case.

### **RQ3: Can VR be used in a home-based rehabilitation system?**

Due to the national lock-down, we changed our direction with the project. We decided to develop a home-based solution with a Wii Balance Board (WBB) and a VR headset. To test this solution, we conducted a user test with five participants. Although this was a small sample size, we got feedback about the user experience, usability, and how to improve the solution. Overall the participants found the experience fun, challenging, easy to use, easy to learn, effective, and efficient. Most of the participants found navigating with the WBB difficult, and two of the participants found the solution somewhat frustrating. We theorize

that this could stem from the WBB not being sensitive enough to control the character satisfactorily, which could affect the whole VR experience. To resolve this, we could conduct further investigation of the WBB or replace the WBB with a more sensitive device. Two out of five participants in the user testing found that using VR in "SkateBalance" gave them discomfort, and these participants also felt mild symptoms of cybersickness. This could occur from the vestibular and visual senses conflicting. The brain can see the movement but does not feel it. There is also the human and technical factors of cybersickness, which is further explained in chapter 5.3 Results from Simulator Sickness Questionnaire and 2.5 Issues and limitations of using VR in rehabilitation.

The current home-based prototype consists of a gaming computer, WBB, and a HMD. We tested with Oculus Rift, but any HMD that fits the criteria displayed in table 2.1 in chapter 2.6 Technical aspect of VRR could be used to decrease the chance of getting cybersickness. There is also the possibility of using a large screen to display the VR environment. According to Rebenitsch and Owen [55], using large screens could increase the chance of getting cybersickness because of the wider field of view (FOV). Three of the participants lost their balance a few times, but none fell or stepped off the WBB. Four of the participant felt overall safe during testing, while one of the participants felt somewhat unsafe and said that he would have liked something to hold on to. Although the user tests were conducted with healthy adults, we have to consider that the home-based prototype is meant to be used by patients with gait and balance issues. There is also the matter of accessibility and pricing, will the patients obtain the equipment themselves or will a therapist provide it for them.

## 6 Conclusion and Future Work

Two virtual reality rehabilitation solutions were created for a biomechatronics lab and a home-based system. Before the Coronavirus pandemic, the project consisted of developing a VR solution for a biomechatronics lab in collaboration with master mechatronics students. Where our solution would control the motion platform, and the mechatronics team solution would control our Unity character's movement and speed in the VR environment. By early March, our prototype was ready for user testing. Our solution could communicate directly with the motion platform and could receive movement and speed from an outside source, e.g the lab control system in the biomechatronics lab. March 13<sup>th</sup>, days before our multi-disciplinary teams would conduct a systems integration test, the University closed down and would not open until April 28<sup>th</sup>. This interfered with all of our plans. Our team could no longer conduct user testing in the biomechatronics lab, the mechatronics team could not work on their solution and user testing became impossible. Therefore, we had to come up with a new plan. Coronavirus pandemic put our whole country in a stand-still; schools and universities closed, people stayed inside to avoid getting sick, and facilities which were deemed non-vital for our community were closed. This also meant that some people could not receive rehabilitation. This is what lead us to explore the possibilities of VRR in-home. We developed and tested a home-based rehabilitation system that we dubbed "SkateBalance" when the government allowed people gathering once again. The system was tested using Oculus Rift and a Nintendo Wii Balance Board (WBB) to determine the feasibility and usability of such a system. The Norwegian Government opened up to gatherings of a maximum of five people; thus, our user tests were conducted with five participants at the beginning of May. From the user tests, we discovered that although the system was enjoyable, there was a risk of cybersickness, and the system needed better security if it is to be used by people with rehabilitation needs.

The following week we integrated our system with the biomechatronics lab. The integration was a success, and communication worked as planned. Five people related to the project tested the system, where none experienced any symptoms of cybersickness. They found the experience to be fun and enjoyable, which we also observed as people laughed and had fun when they tried the biomechatronics lab. In the end, our task of creating the VR solution for the biomechatronics lab was a success. We delivered what was intended on the project, although we would have liked to develop the VR environment further and test the system with the treadmill. The biomechatronics lab will continue to be developed and researched. At this time, it consists of a non-functional treadmill, a force plate to control movement, and collect data, a security harness, and a 6DOF motion platform that can be controlled by Unity. Communication between the systems works and is ready to be developed further by others.

Our hypothesis was: "Virtual reality (VR) rehabilitation can allow patients to do task-

specific and task-varied exercises in a safe environment. Using VR in a biomechatronics lab and home-based rehabilitation systems can be motivating, fun, and will increase adherence to a rehabilitation program.” Further testing is required to determine if the hypothesis is true. Despite the small sample size and limitation on user testing, the initial results indicate that parts of the hypothesis may be true. VR can allow patients to do exercises that are task-specific and task-varied by developing more environments for the VR solution. The user tests on the system also indicated that the participants had fun and enjoyed their experience, which could lead to increased motivation. However, there is a risk of cybersickness when using VR, and the biomechatronics lab can, to some, look intimidating at first glance. Although this depends on the individual, it might make some patients feel unsafe. In the biomechatronics lab, the patient is safely secured by a harness attached to a steel frame that surrounds the motion platform. The home-based system utilized a VR headset to display the VR environment. For safety, a screen could be utilized instead of a VR headset to display the VR environment and something to hold on to when immersed could be provided. Testing on patients was not part of the scope for this master project. The goal was to investigate the feasibility of a VR solution for a biomechatronics lab and home-based environment.

## 6.1 Future Work

The two VRR solutions and related research can provide a foundation for future projects concerning VR rehabilitation and for further development of the biomechatronics lab at the University of Agder. Although the overall goal of the project was accomplished, some features were planned but not integrated into the current systems.

Further development of the VR solutions should aim to create an engaging experience by integrating motivational elements such as points, time, and a storyline. Developing the VR environments could also be considered; the town could include more buildings, and add people and interactions to incorporate social interaction. Background music could also be added.

The motivational properties of VRR should also be researched further does VRR prompt autonomous or controlled motivation? Moreover, how can we harness the motivational properties of VRR and utilize these in rehabilitation programs effectively?

Further user testing should be conducted to verify whether VR is safe and usable in both the biomechatronics lab and home-based system. We suggest that the WBB should be investigated to see whether the sensitivity can be increased, or if more novel technology should be considered for home-based systems.

Furthermore, we suggest exploring the possibility of utilizing the Oculus Quest wirelessly

in the biomechatronics lab. The HTC Vive was the VR headset that fulfilled most of the suggested technical standards that could lower the risk of cybersickness, but it requires cables and a PC to run. The HTC Vive could be used in user testing of the home-based system, but since the University was closed and the HTC Vive could not be moved, this was not possible for us. We suggest that further research involving the HTC Vive in a home-based system should be conducted.

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## **A Interviews with experts in the field of rehabilitation**

### **Interview with professor at the Department of Sport Science and Physical Education at UiA**

On January 29th, we visited Olympiatoppen Sør together with our supervisor Maurice Isabwe to meet with a professor. We went on a tour of Olympiatoppen Sør while we conducted our interview.

#### **Explaining the lab; can you see any areas of use for this system for rehabilitation?**

All of what we are thinking of doing are being done right now and has done it for 20 years. The department needs to know where it wants to go with this lab. VR not connected to a PC, what is the advantage here? S. has not seen that Rexroth 6DOF platform applied to a rehab. What are the possibilities here? Scaling it into a rehab type device in the future?

#### **How does rehabilitation of lower limbs work today? and how about for balance?**

S. worked with balance, they tried lots of ways to train balance. From that, they found that the best solution was the easiest one (just closing one's eyes). Rehab in Norway is not the area where there's the most technology, but there is a lot of need so simple solutions are preferred. People have to go to nursing homes, the patient's mobility is limited so you have to travel to them. So there is a lot of issues around what is the appropriate solution. Is it a simple solution or a high tech solution that is the best?

Maurice: The simplest solution might work well, but they might have a lot of limitations that might be explored. So when you say a solution is complicated or complex today; how about in 5 years? If we find out that this works, perhaps someone will develop a much smaller device later in mass production, and lower the cost of the product. The solution might seem complex today, but at least we need a proof of concept then we might develop technology a little further.

#### **Do you use anything similar in rehabilitation today?**

Magglingen Institute of Sports in Switzerland: Cycling treadmill. Does such a system exist in Norway? Since we come from the tech side of things we need to understand how technology has been developed, to be able to influence how the next technology should be developed. That's why we also need to know how the human body works.

#### **Which direction do you think we should go?**

We should ask the same question to some of the people in healthcare. Kongsgård rehab is one suggestion. Rehab from a car crash, brain injury, long term rehabilitation. If we can make something that makes their quality of life a tiny bit better in the early stages, we may change

their long term prognosis. Where they can go to work again, etc. Balance is typically affected with brain trauma. With stroke it is non-symmetrical. If we can find a more effective way of training/rehabilitating the balance, that could work. Balance training definitely fits into the rehab “umbrella”. This can also lead to more funding. Sunnaas rehabilitation hospital - the director was fascinated with i4Helse, perhaps he is someone we can talk to. S. will also put us in contact with Frode Gallefoss who is the head of research at Sørlandet sykehus, maybe he can connect us to the eco-system at the hospital.

## **Interview with two experts within the field of rehabilitation**

On February 19th, the mechatronics team and our team had a meeting with two experts in the rehabilitation field. Displayed below are our questions and their answers, and notes were taken from the mechatronics teams’ questions.

### **Ser dere noen bruksområder for systemet sånn umiddelbart?**

I.L sitt masterprosjekt: Få en pasient på det utstyret og finne ut hvordan det oppleves, få tilbakemelding kan være kjempe nyttig. Qualitativt studie. En pilot med 4-5 pasienter om møtet med teknologien, dette er noe som Inger Lise kommer til å teste i sin masteroppgave men det blir etter vi er ferdig.

### **Hvilke øvelser gjør dere nå, og kan dette systemet gjøre dette på en annen måte?**

I.L: Det kommer mest ann på hva som feiler de, hvis de er benamputerte så er det veldig viktig å styrke hoftemuskelatur. Belastningsøvelser, trene mage/rygg og det andre beinet er også viktig. For slagpasienter: Prøve å stimulere sensorisk, ta vekten fra side til side, det stimulerer hjernen. Variasjon er viktig. Progresjon er også viktig. Gange: Det er mange av de samme avvikene. Kort skritt med det friske beinet, og langt med det dårlige beinet. Fysioterapeutene prøver å få de til å gå like lenge på begge, få til ”symmetri”. På sykehuset så har de 1 time med terapi, og så får de med seg et program hjem.

### **Hvordan bruker dere dette?**

Vektbæring, balansetrening, og fordi det er gøy.

### **Fungerer det like godt som vanlig rehabilitering?**

Kvaliteten kan bli dårlig, de gjør ikke de riktige bevegelsene. Hvis spillet gjør det slik at du kan ikke ”vinne” om du gjør det feil.

### **Nåværende utstyr som de bruker i dag?**

Jobber mye med å aktivere musklene igjen, og så over på litt styrketrening. Simulere balansecellene.

**Kan dere se for dere at å spillifisere rehabilitering så kan pasienten holde motivasjonen oppe lenger og dermed få bedre utbytte av rehabiliteringen?**

Det kan øke volumet på treningen, som er bra. Spill burde være et supplement.

**Vanlige utfordringer i rehabilitering:**

Motivasjon: Sette opp mål, gi informasjon og feedback, tilpasse treningen slik at de får mestringsfølelse. Spill for motivasjon: bueskyting, curling og utetrening. Det er en del av rehabiliteringen. Quiz. Holde motivasjonen oppe etter utskrivning er vanskeligere. Tenker overføring hele tiden under oppholdet på Kongsgaard.

**Notater fra mekatronikk studentenes spørsmål**

EMG-målinger kan være interessant. Standfase og svingfase, en-gangssyklus, fant oppe disse bevegelsene. Veldig interessant i sammenheng med amputerte iallfall.

Gjerne ha med muligheten til å bruke hendene, som feks på butikken. Systemet må gjøres enkelt og forståelig for eldre som ikke er vant til teknologi. Veldig relevant å teste ut på friske eldre først.

Viktig med VR spill at man har progresjon og vanskelighetsgrader. Tilpasse spillet ut i fra terapeutaens vurdering.

Kommunen har ikke god nok kompetanse når folk blir skrevet ut. Feks amputerte.

De med mest alvorlige problemer kommer til Kongsgaard, de som ikke har alt for mye ”utfall” blir henvist til kommunen.

I.L jobber på sengepost mens S. jobber på poliklinisk.



## **B PACT Analysis**

### **People**

The target users of the biomechatronics lab are persons with disabilities or cognitive problems resulting in issues with balance and/or gait. As well as people in sports, where the system can be used as an evaluation tool with or without the intent of rehabilitation. Other target users are the professionals working with the system such as therapists and researchers

Stakeholders in this project are the people working on the system, hospitals, research facilities, rehabilitation centers, athletes. In our case more specifically; the people working in the motion lab, the mechatronics students, the educational technology students, experts within sports, health, and technology.

### **Activities**

The user will stand on a 6 degrees of freedom (6DOF) platform wearing either a head-mounted display (HMD). Scenarios to be placed in this VR environment is yet to be decided, but it will have to do with keeping and measuring balance using the force plate and moving the 6DOF platform or both balance and gait using the treadmill, force plate, and 6DOF platform. The user will be accompanied by someone who knows how to operate the system and possibly someone with medical knowledge. The frequency of the activity depends on the user. If the system is used for rehabilitation, then the frequency is much more often than say for a one-time user who wants to diagnose or evaluate something. The operator of the system (health professional, a technician) must use the system more frequently and in a different way than the user. The user should only concern themselves with doing the exercise and if necessary stopping the simulation, while the operator must have a deeper knowledge of how to use the system (i.e starting the simulation, adjusting difficulty, stopping).

The simulation must have a quick response time, it must feel as natural as possible when the platform is moving while the simulation is running. This is necessary to minimize the risk of virtual reality sickness and discomfort for the user.

It is necessary to do a risk assessment before testing the system on users. The platform is above ground and without any sort of security around it. If the platform moves too quickly, tilts too much or the user loses his balance, it can lead to injury. We need to find a way to make this system as safe as possible within its boundaries and give the user the possibility to stop the simulation at any time by pressing a physical button.

## Context

The biomechatronics lab is located indoors at the motion lab at the University of Agder. The devices (treadmill, force plate), will be placed on top of the 6DOF platform. The platform is quite tall, approximately 2 m depending on if it is at full height or not. This means that it can be dangerous for people to stand on top of it, especially since the platform will be moving while the user walks on the treadmill wearing a HMD. There will be produced a metal cage in which the user will be attached by a harness.

The rehabilitation system will be controlled from a PC in the same room, and will be connected with cables to try to ensure no latency issues. The activities on the platform will be carried out in the lab, with at least 1 person present to control the simulation and offer support to the user. The lab will predominantly be used for research purposes, and might advance to be used in real cases of rehabilitation later.

## Technology

### Lab System

#### Input

Motion platform When a user is doing rehabilitation exercises, the platform will move in 6 degrees of freedom (6DOF) from the data received from the balance of the user. This might immerse the user in the VR environment, and can facilitate different types of exercises. I.e walking uphill.

Treadmill When a user is doing rehabilitation exercises, i.e gait training, the user will walk on the treadmill. The user inputs the speed by walking, and thus also the distance walked.

Forceplate When a user is doing rehabilitation exercises where in the VR environment the character can move around, i.e skating down a street to train balance, the forceplate will receive the balance center and utilize this to control the motion platform. It might also be utilized for collecting data, i.e for diagnostics or to see progress.

VR headset When a user is doing rehabilitation exercises involving VR, the headset can track the movement of the patient's head.

Lab PC The lab PC will run the whole rehabilitation system, where data will be inputted by a lab operator.

Sensors Many types of sensors can be connected to the rehabilitation system, i.e measuring heart rate, electromyography or pulse.

Motion Capture Cameras Eighteen motion capture cameras are placed around the motion platform, which can receive the movement of the user.

Keyboard The keyboard will be used to input data to the lab PC.

Mouse The mouse will be used to navigate on the screen of the lab PC.

#### Output

Motion platform The motion platform will output movements in 6DOF based on data received from Unity and forceplate.

Treadmill The treadmill will output speed and distance. This can be used to determine for example progress.

Forceplate The forceplate will output the center balance of the user and pressure points.

VR headset Outputs the VR environment.

Lab PC The lab PC gathers and outputs all the data received from sensors and equipment, e.i for diagnostics. It also outputs the VR environment so that the therapist and lab operator can view what happens.

Sensors Many types of sensors can be connected to the rehabilitation system, i.e measuring heart rate, electromyography or pulse.

Motion Capture Cameras Eighteen motion capture cameras are placed around the motion platform, which can output the coordinates of the user. This can be utilized to control a 3D character seen in 3rd person view, or to gather medical data.

## **Communication**

It might be too early in the process to know exactly how the system will communicate, but it is decided that we will try UDP protocol over ethernet cable.

## C Personas and User stories

### Personas

Tore Hansen is 61 years old and suffered an acute stroke three months ago, which left him with reduced functionality on the right side of the body. He has been twice a week going to a physical therapist, where he performs exercises to regain functions in arms and legs to be able to go back to everyday life again. He also has to do exercises at home, but since he is a divorced man, he often does not do the exercises. He struggles with motivation and gets easily frustrated when he doesn't see progress. He struggles with technology and loves fishing and walking in the mountains.

Amanda Pettersen is a 37-year-old woman who lives with her husband, Roger. She is a technological nerd and works as a physical therapist. She tries to implement some technology in training programs, but she can see that it doesn't have the benefits she hoped for.

Cecilie Snarthaug is 16 years old and got in a car accident six months ago. The damage from the crash resulted in the amputation of the left leg and a brain injury. She has been fitted for a prosthetic leg and has been undergoing conventional rehabilitation to rehabilitate balance and walking issues after the brain injury. She has a dog named Bobbi, and her goal is to take Bobbi walking again.

Kurt Viken is a 30 years old researcher. His field of interest is the use of technology in eHealth, specifically for data gathering. He is currently writing a research paper on the use of sensors in the rehabilitation of balance problems in patients with Parkinson's disease.

### User stories

As a patient, I want to be motivated to do my home exercises in order to go back to my daily life as it was before my injury so that I can go back to hiking and fishing.

As a patient, I want to see the progress from rehabilitation, so that I can get motivated to continue doing the exercises and eventually finish rehabilitation.

As a patient, I want to do task-specific exercises in rehabilitation so that I can put the movements in a context.

As a patient, I want to be pain-free when doing rehabilitation exercises so that I can exert my best effort, which will lead to getting rehabilitated faster.

As a patient, I want to feel assured that the exercises I'm doing are being done correctly and that they get me further to my goal of being independent again.

As a researcher, I want easily understood systems so that I can adapt them to my needs with new technological equipment.

As a researcher, I want systems that are usable in order to design and conduct my experiments

without spending unnecessary time on fixing problems or getting frustrated when the system does not work the way I thought it would.

As a physiotherapist, I want my patients to have the best rehabilitation in order for them to regain lost function so that they can live their everyday life or as close to everyday life.

As a physiotherapist, I want to use technology in my training programs in order for the patients to have fun while doing their exercises in order for them not to lose motivation.

As a physiotherapist, I want to feel confident when using rehabilitation systems in order for my patients to use it correctly so that they don't get harmed or do the exercises wrong, which results in prolonged rehabilitation time.

## D Functional Requirements

**Requirement #:** 1                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The product should display a landscape with bumpy roads and slopes  
**Rationale:** To be able to train balance for users who experience balance issues  
**Originator:** Software developer  
**Fit Criterion:** The user will navigate over these bumps and slopes in the road, and they will be able to feel them  
**Customer Satisfaction:** 5    **Customer Dissatisfaction:** 5  
**Priority:** 1                              **Conflicts:**  
**History:** Created March 9th 2020

**Requirement #:** 2                      **Requirement Type:** 26                      **Event:**  
**Description:** The user should be able to navigate the landscape by walking  
**Rationale:** To be able to rehabilitate problems with gait  
**Originator:** Software developer  
**Fit Criterion:** The user will see that the VR world is moving  
**Customer Satisfaction:** 5    **Customer Dissatisfaction:** 5  
**Priority:** 1                              **Conflicts:**  
**History:** Created March 9th 2020

**Requirement #:** 3                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The user should be able to navigate the landscape by leaning forward, backward or sideways  
**Rationale:** To be able to rehabilitate balance problems  
**Originator:** Software developer  
**Fit Criterion:** The user will see that the VR world is moving  
**Customer Satisfaction:** 5    **Customer Dissatisfaction:** 5  
**Priority:** 1                              **Conflicts:**  
**History:** Created March 9th 2020

**Requirement #:** 4                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The product should have main menu, pause menu and finished menu  
**Rationale:** For the product to look more professional and easier to navigate  
**Originator:** Software developer  
**Fit Criterion:** When using the product, the user sees a menu when starting the game, pauses the game and finishes the game  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 3  
**Priority:** 3                              **Conflicts:**  
**History:** Created March 11th 2020

**Requirement #:** 5                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The user should decide which level they want to train in  
**Rationale:** To make the user more challenged in training  
**Originator:** Software developer  
**Fit Criterion:** When the user starts the system, a menu will open and have levels button where the user can choose which level, he/she want to train in  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 3                              **Conflicts:**  
**History:** Created March 11th 2020

**Requirement #:** 6                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The product should display information about bumps or slopes the user is nearing  
**Rationale:** For the user not to be surprised when changes in the road comes  
**Originator:** Software developer  
**Fit Criterion:** When the user is near the bump or slope, information will be displayed  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 3                              **Conflicts:**  
**History:** Created March 10th 2020

**Requirement #:** 7                      **Requirement Type:** 9                      **Event:** 1  
**Description:** The user should be able to stop the game at any point if the user feels unwell or unsafe  
**Rationale:** To be able to keep the user from feeling unwell and prevent falling  
**Originator:** Software developer  
**Fit Criterion:** When the user feels unwell or unsafe, he/she can push a red button on the platform and the system will shut down  
**Customer Satisfaction:** 5    **Customer Dissatisfaction:** 5  
**Priority:** 1                              **Conflicts:**  
**History:** Created March 10th 2020

**Requirement #:** 8                      **Requirement Type:** 26                      **Event:** 1  
**Description:** The user should be able to see his/her progress  
**Rationale:** To be able to motivate the user  
**Originator:** Software developer  
**Fit Criterion:** The product will display a clock, points and other data for the user to see  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 2                              **Conflicts:**  
**History:** Created March 12th 2020

**Requirement #:** 9                      **Requirement Type:** 26                      **Event:** 1  
**Description:** The product should play calming music  
**Rationale:** To be able to reduce the risk of the user getting motion sickness  
**Originator:** Software developer  
**Fit Criterion:** The user will hear calming music while training  
**Customer Satisfaction:** 3    **Customer Dissatisfaction:** 3  
**Priority:** 3                              **Conflicts:**  
**History:** Created March 12th 2020

**Requirement #:** 10                      **Requirement Type:** 26                      **Event:**  
**Description:** The product should have social interaction  
**Rationale:** To be able to prepare the user for everyday life after rehabilitation  
**Originator:** Software developer  
**Fit Criterion:** When the user interacts with the social interaction element and feels more confident after the session  
**Customer Satisfaction:** 3    **Customer Dissatisfaction:** 3  
**Priority:** 3                              **Conflicts:**  
**History:** Created March 12th 2020



## E Non-Functional Requirements

<b>Requirement #:</b> 11	<b>Requirement Type:</b> 11	<b>Event:</b> 1
<b>Description:</b> The product shall be easy for the user to navigate		
<b>Rationale:</b> For the user not to be frustrated when using the product		
<b>Originator:</b> Software developer		
<b>Fit Criterion:</b> After the session, the user and therapist will discuss the experience		
<b>Customer Satisfaction:</b> 5 <b>Customer Dissatisfaction:</b> 5		
<b>Priority:</b> 1 <b>Conflicts:</b>		
<b>History:</b> Created March 9th 2020		

<b>Requirement #:</b> 12	<b>Requirement Type:</b> 12	<b>Event:</b> 1
<b>Description:</b> The user shall feel safe when using the product		
<b>Rationale:</b> So the user can relax and train without feeling unsafe		
<b>Originator:</b> Software developer		
<b>Fit Criterion:</b> After the session, the user and therapist will discuss the experience		
<b>Customer Satisfaction:</b> 5 <b>Customer Dissatisfaction:</b> 5		
<b>Priority:</b> 1 <b>Conflicts:</b>		
<b>History:</b> Created March 9th 2020		

<b>Requirement #:</b> 13	<b>Requirement Type:</b> 26	<b>Event:</b>
<b>Description:</b> The product shall look professional		
<b>Rationale:</b> So that the user and therapist wants to use it		
<b>Originator:</b> Software developer		
<b>Fit Criterion:</b> After using the product the user should feel like the product is trustworthy		
<b>Customer Satisfaction:</b> 4 <b>Customer Dissatisfaction:</b> 4		
<b>Priority:</b> 2 <b>Conflicts:</b>		
<b>History:</b> Created March 9th 2020		

**Requirement #:** 14      **Requirement Type:** 11      **Event:** 1  
**Description:** The product shall be used by people with little to no training  
**Rationale:** So that the users and therapist don't need to spend a long time learning how to use the product  
**Originator:** Software developer  
**Fit Criterion:** A survey that will show how long it took before the user or therapist learned to use it  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 2                      **Conflicts:**  
**History:** Created March 10th 2020

**Requirement #:** 15      **Requirement Type:** 26      **Event:**  
**Description:** The product shall be universal design  
**Rationale:** So that the product can be accessible to as many people as possible so that they can participate and use the product regardless of functional ability  
**Originator:** Software developer  
**Fit Criterion:** Survey that will show that it is accessible to all people  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 3                      **Conflicts:**  
**History:** Created March 10th 2020

**Requirement #:** 16      **Requirement Type:** 13      **Event:** 2  
**Description:** The product shall be used in a lab  
**Rationale:** So that the user can get help from therapist if needed  
**Originator:** Software developer  
**Fit Criterion:** User testing to find out if the product can be used at a lab  
**Customer Satisfaction:** 5    **Customer Dissatisfaction:** 5  
**Priority:** 1                      **Conflicts:**  
**History:** Created March 9th 2020

**Requirement #:** 17      **Requirement Type:** 13      **Event:** 2  
**Description:** The product shall be easy to use by people between the age of 13 and 80+  
**Rationale:** So that all kinds of people can use the product  
**Originator:** Software developer  
**Fit Criterion:** A survey shall show that people of every age finds it easy to use the product  
**Customer Satisfaction:** 4    **Customer Dissatisfaction:** 4  
**Priority:** 2                      **Conflicts:**  
**History:** Created March 9th 2020

**Requirement #:** 18**Requirement Type:** 13**Event:** 2**Description:** The product shall be used at home**Rationale:** So that the user can train at home and not go to a training facility**Originator:** Software developer**Fit Criterion:** User testing to find out if the product can be used at home**Customer Satisfaction:** 5 **Customer Dissatisfaction:** 5**Priority:** 1**Conflicts:****History:** Created March 18th 2020

# F TerrainObserver

```
public class TerrainObserver : MonoBehaviour
{
    // Settings
    public bool estimateLocalPlane = true;
    public float h0;

    // TxData
    public float h;
    public float rotX;
    public float rotZ;

    // RxData
    public float speedVertical;
    public float speedHorizontal;

    public Vector3 nVector;
    public float checkDistance = 2;
    public float checkRadius = 0.5f;
    public int nChecks = 20;
    public int nHits = 0;

    // UDP related
    public int nRecv;
    public byte[] rxBuffer, txBuffer;

    private IPEndPoint remoteEP, localEP;

    private Vector3[] origin, direction;

    private RaycastHit[] hits;

    private Matrix<float> A, N, V;

    private UdpClient socket;

    // Start is called before the first frame update
    void Start()
    {
        socket = new UdpClient(4000);
    }
}
```

```
        socket.BeginReceive(new AsyncCallback(OnUdpData), socket);

    }

    // Update is called once per frame
    void FixedUpdate()
    {
        // Construct raycast hit array
        hits = new RaycastHit[nChecks];
        origin = new Vector3[nChecks];
        direction = new Vector3[nChecks];

        // Terrain height
        h = (transform.position + transform.TransformDirection(Vector3.down)).y - h0;

        Vector3 v = checkRadius*Vector3.forward;

        // Find plane with Raycast
        http://thehidensignal.com/unity-angle-of-sloped-ground-under-player/

        // Reset hit count
        nHits = 0;
        for (int i = 0; i < nChecks; i++)
        {
            // Raycast check origin in global space
            origin[i] = transform.position + transform.TransformDirection(
                0.5f * Vector3.down + Quaternion.Euler(0, (float)i / nChecks * 360 , 0) * v
            );

            // Raycast check direction in global space
            direction[i] = transform.TransformDirection(Vector3.down);

            // Cast ray
            if (Physics.Raycast(origin[i], direction[i], out hits[i], checkDistance))
            {
                // Count number of hits
                nHits = nHits + 1;

                // Draw result
                Debug.DrawRay(origin[i], direction[i] * hits[i].distance, Color.red);
            }
        }
    }
}
```

```
// Estimate plane based on 3 or more hitpoints
if (nHits >= 3)
{
    A = Matrix<float>.Build.Dense(nHits, 4);

    // Fill data
    for (int i = 0; i < nHits; i++)
    {
        // Calibration of the Norwegian motion laboratory using
        conformal geometric algebra,
        Olav Heng med ml.
        // https://dl.acm.org/doi/abs/10.1145/3095140.3097285?casa
        token=a4BDviqGwywAAAAA:XA7wPapL0sY-
        fAxfMJvYaKG7JTrUP5AlYQvHikOBizZa2iLkgZfVGdlpZNA1rXSJPqbIaI
        EeByi
        // https://github.com/sondre1988/matlab-functions/blob/mas
        er/src/PlaneFitCGA.m

        // Hit point in global space and local space
        Vector3 hitPointGlobal = origin[i] + direction[i] *
        hits[i].distance;
        Vector3 hitPointLocal =
        transform.InverseTransformPoint(hitPointGlobal);

        Vector3 point;
        if (estimateLocalPlane)
        {
            point = hitPointLocal;
        }
        else
        {
            point = hitPointGlobal;
        }

        // RegressionProcess
        // Stack hit points
        A[i, 0] = point.x;
        A[i, 1] = point.y;
        A[i, 2] = point.z;
        A[i, 3] = -1;

        // Solve using Eigenvalue decomposition
```

```
N = A.Transpose() * A;
Evd<float> evd = N.Evd();

V = evd.EigenVectors;

// Get normal vector
Vector<float> sol = V.Column(0);

// Fix signs
if (sol[1] < 0)
{
    sol = -sol;
}

nVector.x = sol[0];
nVector.y = sol[1];
nVector.z = sol[2];

nVector.Normalize();

// Calculate angles of plane relative to world
rotX = Mathf.Atan2(nVector.z, nVector.y);
rotZ = Mathf.Atan2(nVector.x, nVector.y);
}
}

// Send data to Python Middleware
MemoryStream txStream = new MemoryStream();
BinaryWriter txWriter = new BinaryWriter(txStream);

// Encode message to byte array
txWriter.Write(h);
txWriter.Write(rotX);
txWriter.Write(rotZ);

txBuffer = txStream.ToArray();

// Set speed on player
playerController player = GetComponent<playerController>();
player.speedHorizontal = speedHorizontal;
player.speedVertical = speedVertical;
```

```
}  
void OnUdpData(IAsyncResult result)  
{  
    // this is what had been passed into BeginReceive as the second  
    parameter:  
    UdpClient socket = result.AsyncState as UdpClient;  
  
    // Recieve data from remote source  
    rxBuffer = socket.EndReceive(result, ref remoteEP);  
  
    // Convert data  
    MemoryStream rxStream = new MemoryStream(rxBuffer);  
    BinaryReader rxReader = new BinaryReader(rxStream);  
  
    speedVertical = rxReader.ReadSingle();  
    speedHorizontal = rxReader.ReadSingle();  
  
    // Echo data back to remote  
    socket.Send(txBuffer, txBuffer.Length, remoteEP);  
  
    // Schedule the next receive operation once reading is done:  
    socket.BeginReceive(new AsyncCallback(OnUdpData), socket);  
  
    // Increment counter  
    nRecv = nRecv + 1;  
}  
  
private void OnApplicationQuit()  
{  
    socket.Close();  
}  
}
```



## G TxLabControlMessages

```
class TxUdp(ctypes.Structure):
    _fields_ = [
        # Udp Access Key
        ('iUdpKey', ctypes.c_uint32),

        # Activity counter
        ('iCounter', ctypes.c_uint32),

        # Mode command (inactive as for now...)
        ('eModeCmd', ctypes.c_uint32),

        # EM8000 position commands in [m]
        ('em8000_surge_cmd', ctypes.c_float),
        ('em8000_sway_cmd', ctypes.c_float),
        ('em8000_heave_cmd', ctypes.c_float),

        # EM8000 euler angle commands in [rad]
        ('em8000_roll_cmd', ctypes.c_float),
        ('em8000_pitch_cmd', ctypes.c_float),
        ('em8000_yaw_cmd', ctypes.c_float),

        # EM8000 position commands in [m]
        ('em8000_surge_t_cmd', ctypes.c_float),
        ('em8000_sway_t_cmd', ctypes.c_float),
        ('em8000_heave_t_cmd', ctypes.c_float),

        # EM8000 euler angle commands in [rad]
        ('em8000_roll_t_cmd', ctypes.c_float),
        ('em8000_pitch_t_cmd', ctypes.c_float),
        ('em8000_yaw_t_cmd', ctypes.c_float),

        # EM1500 position commands in [m]
        ('em1500_surge_cmd', ctypes.c_float),
        ('em1500_sway_cmd', ctypes.c_float),
        ('em1500_heave_cmd', ctypes.c_float),

        # EM1500 euler angle commands in [rad]
        ('em1500_roll_cmd', ctypes.c_float),
        ('em1500_pitch_cmd', ctypes.c_float),
        ('em1500_yaw_cmd', ctypes.c_float),
```

```
# EM1500 position commands in [m]
('em1500_surge_t_cmd', ctypes.c_float),
('em1500_sway_t_cmd', ctypes.c_float),
('em1500_heave_t_cmd', ctypes.c_float),

# EM1500 euler angle commands in [rad]
('em1500_roll_t_cmd', ctypes.c_float),
('em1500_pitch_t_cmd', ctypes.c_float),
('em1500_yaw_t_cmd', ctypes.c_float),

# Comau robot joint speed commands in [rad/s]
('comau_q1_t_cmd', ctypes.c_float),
('comau_q2_t_cmd', ctypes.c_float),
('comau_q3_t_cmd', ctypes.c_float),
('comau_q4_t_cmd', ctypes.c_float),
('comau_q5_t_cmd', ctypes.c_float),
('comau_q6_t_cmd', ctypes.c_float),

# Winch speed command in [m/s]
('winch_l_t_cmd', ctypes.c_float)
]
```

# H RxLabControlMessages

```
class RxUdp(ctypes.Structure):
    _fields_ = [
        # Current operation mode and PLC time [s]
        ('eMode', ctypes.c_uint32),
        ('t', ctypes.c_float),

        # Comau angle feedback in [rad]
        ('comau_q1', ctypes.c_float),
        ('comau_q2', ctypes.c_float),
        ('comau_q3', ctypes.c_float),
        ('comau_q4', ctypes.c_float),
        ('comau_q5', ctypes.c_float),
        ('comau_q6', ctypes.c_float),

        # Comau angular speed feedback in [rad/s]
        ('comau_q1_t', ctypes.c_float),
        ('comau_q2_t', ctypes.c_float),
        ('comau_q3_t', ctypes.c_float),
        ('comau_q4_t', ctypes.c_float),
        ('comau_q5_t', ctypes.c_float),
        ('comau_q6_t', ctypes.c_float),

        # Winch wire length in [m] and speed in [m/s]
        ('winch_l', ctypes.c_float),
        ('winch_l_t', ctypes.c_float),

        # EM8000 translational positions in [m]
        ('em8000_surge', ctypes.c_float),
        ('em8000_sway', ctypes.c_float),
        ('em8000_heave', ctypes.c_float),

        # EM8000 euler angles in [rad]
        ('em8000_roll', ctypes.c_float),
        ('em8000_pitch', ctypes.c_float),
        ('em8000_yaw', ctypes.c_float),

        # EM8000 translational velocities in [m/s]
        ('em8000_surge_t', ctypes.c_float),
        ('em8000_sway_t', ctypes.c_float),
        ('em8000_heave_t', ctypes.c_float),
```

```
# EM8000 euler velocites in [rad/s]
('em8000_roll_t', ctypes.c_float),
('em8000_pitch_t', ctypes.c_float),
('em8000_yaw_t', ctypes.c_float),

# EM8000 translational accelerations in [m/s^2]
('em8000_surge_tt', ctypes.c_float),
('em8000_sway_tt', ctypes.c_float),
('em8000_heave_tt', ctypes.c_float),

# EM8000 euler accelerations in [rad/s^2]
('em8000_roll_tt', ctypes.c_float),
('em8000_pitch_tt', ctypes.c_float),
('em8000_yaw_tt', ctypes.c_float),

# MRU1 (EM8000) translational positions in [m]
('mru1_surge', ctypes.c_float),
('mru1_sway', ctypes.c_float),
('mru1_heave', ctypes.c_float),

# MRU1 (EM8000) euler angles in [rad]
('mru1_roll', ctypes.c_float),
('mru1_pitch', ctypes.c_float),
('mru1_yaw', ctypes.c_float),

# MRU1 (EM8000) translational velocites in [m/s]
('mru1_surge_t', ctypes.c_float),
('mru1_sway_t', ctypes.c_float),
('mru1_heave_t', ctypes.c_float),

# MRU1 (EM8000) body velocities in [rad/s]
('mru1_wx', ctypes.c_float),
('mru1_wy', ctypes.c_float),
('mru1_wz', ctypes.c_float),

# EM1500 translational positions in [m]
('em1500_surge', ctypes.c_float),
('em1500_sway', ctypes.c_float),
('em1500_heave', ctypes.c_float),

# EM1500 euler angles in [rad]
('em1500_roll', ctypes.c_float),
('em1500_pitch', ctypes.c_float),
```

```
( 'em1500_yaw', ctypes.c_float),

# EM1500 translational velocites in [m/s]
( 'em1500_surge_t', ctypes.c_float),
( 'em1500_sway_t', ctypes.c_float),
( 'em1500_heave_t', ctypes.c_float),

# EM1500 euler velocites in [rad/s]
( 'em1500_roll_t', ctypes.c_float),
( 'em1500_pitch_t', ctypes.c_float),
( 'em1500_yaw_t', ctypes.c_float),

# EM1500 translational accelerations in [m/s^2]
( 'em1500_surge_tt', ctypes.c_float),
( 'em1500_sway_tt', ctypes.c_float),
( 'em1500_heave_tt', ctypes.c_float),

# EM1500 euler accelerations in [rad/s^2]
( 'em1500_roll_tt', ctypes.c_float),
( 'em1500_pitch_tt', ctypes.c_float),
( 'em1500_yaw_tt', ctypes.c_float),

# MRU1 (EM1500) translational positions in [m]
( 'mru1_surge', ctypes.c_float),
( 'mru1_sway', ctypes.c_float),
( 'mru1_heave', ctypes.c_float),

# MRU1 (EM1500) euler angles in [rad]
( 'mru1_roll', ctypes.c_float),
( 'mru1_pitch', ctypes.c_float),
( 'mru1_yaw', ctypes.c_float),

# MRU1 (EM1500) translational velocites in [m/s]
( 'mru1_surge_t', ctypes.c_float),
( 'mru1_sway_t', ctypes.c_float),
( 'mru1_heave_t', ctypes.c_float),

# MRU1 (EM1500) body velocities in [rad/s]
( 'mru1_wx', ctypes.c_float),
( 'mru1_wy', ctypes.c_float),
( 'mru1_wz', ctypes.c_float)
]
```

# I playerController

```
public class playerController : MonoBehaviour
{
    // Inputs
    public float maxSpeed = 4;
    public float speedVertical;
    public float speedHorizontal;

    public float overallSpeed;
    public float gravity = 0f;
    private CharacterController controller;

    private Vector3 playerMotion = Vector3.zero;

    // Start is called before the first frame update
    void Start()
    {
        controller = GetComponent<CharacterController>();
    }

    // Update is called once per frame
    void FixedUpdate()
    {
        if (controller.isGrounded)
        {
            // Manipulate player direction
            transform.RotateAroundLocal(Vector3.up, maxSpeed * 0.1f *
                (speedHorizontal + Input.GetAxis("Horizontal")) *
                Time.fixedDeltaTime);

            playerMotion = maxSpeed*(speedVertical +
                Input.GetAxis("Vertical")) *
                transform.TransformDirection(Vector3.forward);

            //Debug.Log(moveDirection);
        }

        // Gravity
        playerMotion.y -= gravity;

        // Move player
    }
}
```

```
    controller.Move(playerMotion * Time.fixedDeltaTime);  
    overallSpeed = controller.velocity.magnitude;  
  
}
```

## **J Assets used in Unity Project**

For this project we chose to use assets from Unity Asset Store. The assets used, were free assets with a Extension Asset license when downloaded.

### **Simple Gems Ultimate Animated Customizable Pack**

<https://assetstore.unity.com/packages/3d/props/simple-gems-ultimate-animated-customizable-pack-73764>

### **Score and Time**

<https://assetstore.unity.com/packages/audio/sound-fx/score-and-time-59255>

### **Skateboard PBR**

<https://assetstore.unity.com/packages/3d/props/skateboard-pbr-72179>

### **Simple Sky - Cartoon assets**

<https://assetstore.unity.com/packages/3d/simple-sky-cartoon-assets-42373>

### **Simple City pack plain**

<https://assetstore.unity.com/packages/3d/environments/urban/simple-city-pack-plain-100348>

### **Low poly European City Pack**

<https://assetstore.unity.com/packages/3d/environments/urban/low-poly-european-city-pack-71042>

### **LowPoly Environment Pack**

<https://assetstore.unity.com/packages/3d/environments/landscapes/lowpoly-environment-pack-99479>



# K Pre Interview

## Spørsmål før test

1. Kjønn:

- Kvinne  
 Mann  
 Annet

2. Alder:

- 19  
 20-24  
 25-29  
 30-34  
 35-39  
 40-44  
 45+

3. Har du tidligere erfaring med VR ?

- Ja  
 Nei

Hvis ja, hvilket system?

4. Har du tidligere prøvd trening med VR eller andre verktøy? (eks. Wii Fit, Kinect sports)

- Ja  
 Nei

Hvis ja, hvilke verktøy?

5. Har du gjort rehabiliteringsøvelser tidligere?

- Ja  
 Nei

6. Har du eller driver du med trening/sport?

- Ja, jeg har drevet med trening/sport.  
 Ja, jeg driver med trening/sport.  
 Nei, jeg driver ikke med trening/sport.

Hvis ja, hva slags trening/idrett?

7. Spiller du eller har du spilt videospill?

- Ja, jeg har spilt videospill.  
 Ja, jeg spiller videospill.  
 Nei, jeg har ikke spilt videospill.

Hvis ja, hvilket system har du spilt på/spiller på?

8. Hvor teknisk anlagt vil du si at du er på en skala fra 1 – 5?

*Hvor 1 = Veldig dårlig og 5 = Veldig god*

1. Veldig dårlig  
 2. Dårlig  
 3. Nøytral  
 4. God  
 5. Veldig god

# L Simulator Sickness Questionnaire

## SSQ før og etter test

Føler du motion sickness nå?

- Ja  
 Nei

Sett ring rundt hvor mye hvert symptom nedenfor påvirker deg nå.  
0= Ikke i det hele tatt    1= Mild    2= Moderat    3 = Alvorlig

1. Generelt ubehag	0	1	2	3
2. Fatigue	0	1	2	3
3. Hodepine	0	1	2	3
4. Øyestress	0	1	2	3
5. Vanskelig å fokusere	0	1	2	3
6. Økt spyttproduksjon	0	1	2	3
7. Svetteing	0	1	2	3
8. Kvalme	0	1	2	3
9. Konsentrasjonsvansker	0	1	2	3
10. Press i hodet	0	1	2	3
11. Uskarpt syn	0	1	2	3
12. Svimmelhet (øynene åpne)	0	1	2	3
13. Svimmelhet (øynene lukket)	0	1	2	3
14. Vertigo*	0	1	2	3
15. Mage bevissthet**	0	1	2	3
16. Raping	0	1	2	3

\*Vertigo oppleves som tap av orientering med hensyn til vertikal loddrett.

\*\*Mage bevissthet brukes vanligvis for å indikere en følelse av ubehag som bare mangler kvalme.

# M Post Interview

## Spørsmål etter test

1. Å bruke Skatebalance er en frustrerende opplevelse

*Hvor 1 = Veldig uenig og 7 = Veldig enig*

- 1. Veldig uenig
- 2. Uenig
- 3. Litt uenig
- 4. Nøytral
- 5. Litt enig
- 6. Enig
- 7. Veldig enig

2. Skatebalance er enkel å bruke

*Hvor 1 = Veldig uenig og 7 = Veldig enig*

- 1. Veldig uenig
- 2. Uenig
- 3. Litt uenig
- 4. Nøytral
- 5. Litt enig
- 6. Enig
- 7. Veldig enig

3. Å navigere ved hjelp av Wii balansebrett er enkelt

*Hvor 1 = Veldig uenig og 7 = Veldig enig*

- 1. Veldig uenig
- 2. Uenig
- 3. Litt uenig
- 4. Nøytral
- 5. Litt enig
- 6. Enig
- 7. Veldig enig

4. Jeg følte meg sikker på min trygghet når jeg bruke Skatebalance

*Hvor 1 = Veldig uenig og 7 = Veldig enig*

- 1. Veldig uenig
- 2. Uenig
- 3. Litt uenig
- 4. Nøytral
- 5. Litt enig
- 6. Enig
- 7. Veldig enig

5. Bruk av VR i Skatebalance gav meg ubehag

*Hvor 1 = Veldig uenig og 7 = Veldig enig*

- 1. Veldig uenig
- 2. Uenig
- 3. Litt uenig
- 4. Nøytral
- 5. Litt enig
- 6. Enig
- 7. Veldig enig

6. Hvordan var opplevelsen av å bruke VR og Wii balansebrett på denne måten?

7. Har du noen forslag til endringer?