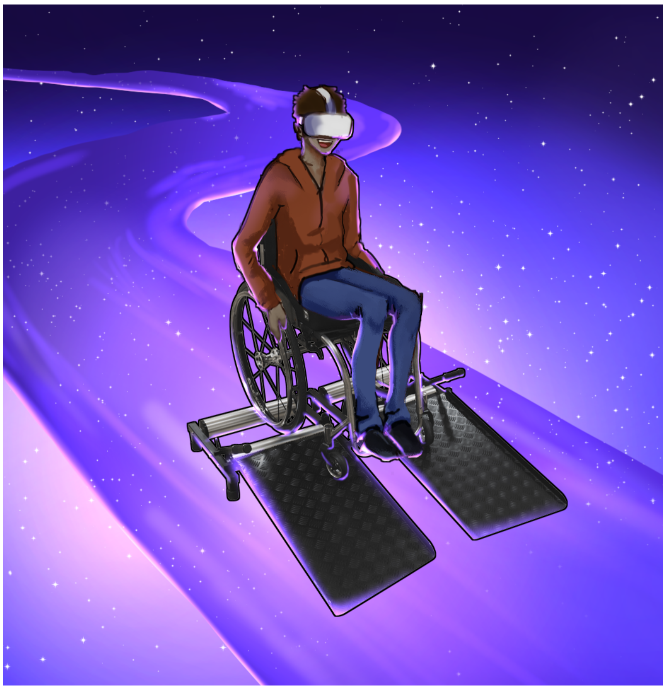
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Engineering Cybernetics

Embla Flatlandsmo

Novel VR Exergaming for Wheelchair Users: Cybersickness and User Experience

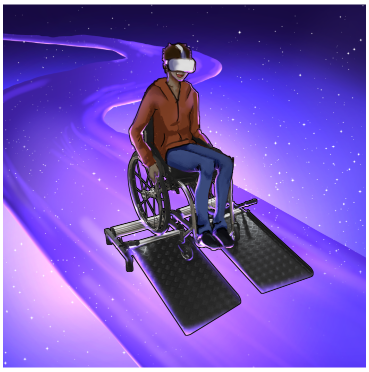
Master's thesis in Cybernetics and Robotics
Supervisor: Damiano Varagnolo
Co-supervisor: Julia Kathrin Baumgart & Roya Doshmanziari
June 2023



NTNU
Norwegian University of
Science and Technology

Embla Flatlandsmo

Novel VR Exergaming for Wheelchair Users: Cybersickness and User Experience



Master's thesis in Cybernetics and Robotics
Supervisor: Damiano Varagnolo
Co-supervisor: Julia Kathrin Baumgart & Roya Doshmanziari
June 2023

Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Engineering Cybernetics

NTNU
Norwegian University of
Science and Technology

Preface

The journey that culminated in this master's thesis has been a fun adventure filled with enlightenment and personal growth. It began as a desire to create something impactful that extends beyond the NTNU campus grounds, and which can positively influence many lives. I was lucky to find a topic that let me pursue my interests in embedded systems and low(ish)-level programming, a field I have grown very fond of during my academic journey and am excited to work in full-time after my graduation.

Coming into my final year at NTNU, I was fortunate enough to already have received multiple job offers in my field of interest. This in turn gave me the freedom to make choices about my final year project that were less about academic necessity and more about personal motivation and a desire to make a meaningful contribution. I was driven not only by the potential to learn a lot of new things, although it was a welcomed byproduct, but rather by the idea of creating something that could potentially bring a positive change in the lives of others.

The choice of my thesis topic was serendipitous. In the fall, I struggled to find a connection and excitement for most of the officially listed project ideas, many of which either felt too corporate or insufficiently impactful to me. It was in one of the initial conversations with my supervisor, Damiano, that the seed that would later become the topic of my thesis was planted. The potential of developing a VR exergame platform for wheelchair users captured my imagination instantly. It resonated with my wish to work on a project that I found both interesting and meaningful. The possibility of this technology improving lives and promoting inclusivity in fitness drew me in and fueled my commitment to bring this concept to fruition.

This thesis is an embodiment of my work and commitment to a technology that I personally find very promising. Throughout this endeavor, I remained motivated by the clear understanding that the harder I worked on the project, the greater potential it had for positively impacting lives. The journey has been somewhat solitary and challenging, but extremely gratifying.

I am happy to have been able to contribute to this exciting intersection of technology and inclusive fitness. I sincerely hope that you enjoy reading this thesis as much as I have loved the process of researching and writing it.

Acknowledgements

As I reflect on the journey of completing this thesis, I would like to express my gratitude to a number of individuals whose assistance and support were invaluable:

First off, I would like to extend a sincere thanks to my supervisor, Damiano Varagnolo. Your guidance throughout this project was incredibly valuable. You consistently led me in a positive direction and I am grateful for the way you encouraged me to explore the areas that interested me the most. You offered a balance of direction and freedom that has made this journey both very enjoyable and very rewarding. You have been an excellent supervisor, and I'm grateful to have had the opportunity to learn from you.

Thanks to Julia K. Baumgart for having provided great feedback on my work as well as insights about sports science, wheelchair users and experiment design. I am truly grateful for your involvement in my research journey and your contribution to the project.

Thanks to Roya Doshmanziari for being available to answer my questions! I appreciate that you have taken the time to help me out when I felt that I needed it.

Thanks to the ITK workshop, in particular Glenn Angell for being readily available and coming up with inventive ideas to solve my practical problems.

My deepest gratitude goes out to my family – my mother, father, and sister – for their consistent and unwavering support throughout this academic journey. To my mother, your ever-present cheerfulness has been a source of light, lifting my spirits even in the most challenging times. My father, your encouragement and genuine interest in my work have given me the drive to strive for the best. Last but certainly not least, a special thanks to my sister, Edda, whose unending support and enthusiastic cheering always bolstered my confidence. Your encouragement was instrumental in my journey!

Finally, thanks to my boyfriend Mats for reminding me to take breaks every now and again. Also, thanks for giving me a pat on the back every time you heard that deep sigh of frustration when the code change didn't fix my bug... *again.*

Executive Summary

Wheelchair users are more at risk of living a sedentary lifestyle when compared to the general population. This means that they are at a higher risk of lifestyle-related illnesses such as obesity, diabetes and cardiovascular diseases. Exercise games, or exergames, have shown to increase an individual's motivation to exercise, and virtual reality (VR) games have been shown to elicit high levels of enjoyment and motivation in participants. In an attempt to provide an easily accessible and fun way for wheelchair users to exercise, an exergame platform that enables wheelchair users to exercise in a VR environment has been created and evaluated in this thesis. This platform, that structurally is as in the cover picture of the thesis, has been evaluated in terms of its capabilities of captivating users. More specifically, this evaluation has been done by answering the three research questions:

RQ1. How do users' cybersickness symptoms and sense of enjoyment vary with the way the wheelchair wheels' rotational speeds are processed in the exergame platform?

RQ2. What factors contribute to a good user experience in a VR wheelchair simulator, and how do they relate to the design and implementation of the exergame platform?

RQ3. What are the characteristics of individuals who experience cybersickness in response to the exergame platform, and how do they differ from those who do not experience cybersickness?

The exergame platform that was developed for this thesis has been thoroughly documented. Able-bodied study participants tested three different versions of the device, where the first version of the device had 6 participants, the second version had 5 participants and the third version had 26 participants. Data was collected in all the test rounds and included metrics such as in-game movement speed, Simulator Sickness Questionnaire (SSQ) score, Short Physical Activity Enjoyment Scale (PACES-S) score, heart rate (HR), susceptibility to motion sickness as well as VR gaming experience.

Findings from answering RQ1 suggest that the processing of wheelchair wheels' rotational speeds does not seem to significantly influence users' enjoyment or cybersickness levels. After having done improvements on the device based on users' feedback, no notable changes in either PACES-S or SSQ were found. This points to the possibility that other factors such as the gameplay itself may be more impactful to both user enjoyment and cybersickness levels.

In addressing RQ2, a strong inverse relationship between the SSQ and PACES-S scores was found, indicating that the absence of cybersickness significantly contributes to a positive user experience. Heart rate appeared to be positively correlated with PACES-S score and negatively correlated with SSQ score, suggesting that cybersickness might limit exercising at higher intensity levels. Additionally, qualitative feedback suggests that the controls of the device needs to feel realistic and intuitive. The findings suggest that the exergame platform needs to minimize cybersickness and offer realistic and intuitive controls to ensure a good user experience and enable players to exercise at higher intensity levels.

Analysis of RQ3 identified motion sickness susceptibility and gender as major predictors of cybersickness. Those who experienced significant cybersickness were unable to achieve high in-game movement speeds, thus impacting their potential benefit from the exergame platform. The data also showed a weak trend that increased exposure to VR reduces cybersickness symptoms, but more data is needed to confirm this.

This thesis provides valuable insights into the challenges and potential solutions for enhancing user experience for the VR wheelchair exergame platform. Further work recommends evaluating different types of games on the exergame platform, comparing users' performance in the VR exergame to non-VR exergames, and conducting a study on wheelchair users.

Table of Contents

List of Tables

List of Figures

Abbreviations

Abbreviation	Description
VR	Virtual Reality
ESD	Electrostatic Discharge
HID	Human Interface Device
PC	Personal Computer
IIR	Infinite Impulse Response
SSQ	Simulator Sickness Questionnaire
PACES-S	Short Physical Activity Enjoyment Scale
VRISE	Virtual Reality Induced Sickness Effects
VRSQ	Virtual Reality Sickness Questionnaire
EDA	Electrodermal Activity
PACES	Physical Activity Enjoyment Scale
GDPR	General Data Protection Regulation
NTNU	Norwegian University of Science and Technology
SD	Standard Deviation
FPS	First Person Shooter
IPD	Interpupillary Distance

1 Introduction

1.1 Background

Physical activity offers numerous benefits, serving as a potent behaviour to enhance both physical and mental well-being [1][2]. Engaging in regular exercise has been associated with an improved quality of life and has even been shown to positively correlate with reduced unemployment rates [3]. The burden on healthcare systems resulting from widespread physical inactivity [4] emphasizes the societal significance of promoting and facilitating physical activity for all individuals. Given physical activity's profound impact on life satisfaction, it follows that society should promote an environment that encourages and enables widespread participation in regular exercise.

The estimated population of wheelchair users in Norway is approximately 50000 individuals [5]. The World Health Organization estimates that 80 million, or 1% of people worldwide, are likely to require a wheelchair to assist their mobility [6]. For individuals with physical disabilities, adopting an active lifestyle holds particular significance. A sedentary lifestyle among this population heightens the risk of preventable health conditions such as obesity, diabetes and cardiovascular diseases [7]. Despite this knowledge, the prevalence of physical inactivity among individuals with physical disabilities is strikingly higher, with three to five times more individuals refraining from engaging in exercise when compared to the general population [8]. This prompts the question of how we can effectively promote increased physical activity among wheelchair users with the particular focus on the Norwegian population.

One potential approach to address the prevalent issue of physical inactivity among wheelchair users is to leverage recent advancements in Virtual Reality (VR) technology as a means of promoting and maintaining physical activity levels. VR refers to a computer-generated environment that replicates a physical presence in real or imagined worlds, enabling users to control a visual representation of their bodies to complete various tasks [9]. Research has demonstrated the positive effects of employing technological solutions to enhance physical activity levels among the general population [10]. Limited research has been conducted on individuals with physical disabilities in the field of both VR and exercise games, or exergames, but preliminary findings are encouraging. One study concluded that there is a major demand for applications, particularly exergames, that help include disabled people in society and to improve their life conditions [11]. A more recent study has concluded that exergaming seems to be a promising aerobic exercise mode for wheelchair-dependent persons with a spinal cord injury [12]. Finally, it was has been suggested that engaging in VR games elicits a high level of enjoyment and motivation in participants [13]. Currently, there are not enough VR solutions made specifically to increase physical activity in people with physical disabilities. This means there is a great opportunity to use these technologies to encourage a more active and healthier lifestyle.

VR technologies commonly encompass features that facilitate social interaction, offering notable benefits for peer engagement [14]. Additionally, the inclusion of multiplayer capabilities within VR platforms presents opportunities for collective exercise experiences. The opportunity to play exergames in multiplayer mode leads to better fitness outcomes than when playing alone [15]. Although creating a multiplayer experience will not be the focus of this thesis, the work that has been done will be a step in the direction to enabling multiplayer gaming.

In short, the utilization of VR technology holds considerable potential for enhancing physical activity among wheelchair users or other people with physical disabilities. The existing evidence showcases positive outcomes associated with employing technological interventions to augment physical activity, resulting in heightened enjoyment and motivation. These findings highlight a clear opportunity to enhance the well-being and overall quality of life within the target demographic. The social interaction and multiplayer capabilities inherent in VR technology offer promising avenues to address the social activity and mental health challenges often faced by young adults with physical disabilities. Further research and development of VR solutions for wheelchair users present a promising pathway for fostering a more active and healthy lifestyle among this population.

1.2 Wheelchair Simulators

Some research has already been done on technology that allows a wheelchair user to navigate in a game by propelling a real-life wheelchair. In general, these setups are commonly referred to as *wheelchair simulators* [16]. They may be made for either manual or electrical wheelchairs. In manual wheelchair simulators, the user propels the wheels by using their hands, while in electrical wheelchair simulators, the user often uses a joystick.

The first research paper on a manual wheelchair simulator (one in which you use your hands to propel the wheelchair wheels, thus moving in the virtual environment) was published in 2000 by O'Connor et al[17]. The paper focused on how a users' propulsion patterns and heart rate varied between users who exercised while playing or not playing a game. This setup did not feature a VR headset but rather a monitor. The study suggested that exergames for wheelchair users might help them exercise both more vigorously and more regularly [17].

Most research that has been done on VR wheelchair simulators are about the qualitative feeling of the user, such as the a sense of presence [18] or the able-bodied users' implicit bias towards wheelchair users [19]. One study has tested information recall in a VR wheelchair simulator [20] while another one investigated the use of VR wheelchair simulators in the development of accessible buildings [21]. Overall, no work has been done so far to assess the suitability of VR wheelchair simulators in the context of training.

Overall, research work seems to have been done both in the area of exercise and VR in the context of wheelchair simulators, but no studies have been published assessing both at the same time. That is, no studies have examined the use of VR games as a manual wheelchair exercise tool.

1.3 Problem Description

The development of technology that caters to the unique needs of wheelchair users, specifically providing them with a tailored VR experience, holds great potential in positively impacting the lives of many people. As such, the primary aim of this thesis is to assess the viability of employing such VR exergames as a means to promote physical activity among wheelchair users. The resulting device will serve as a platform for exercise games, which will from here on out be referred to as exergames. The overarching goal of the thesis gives rise to several research questions:

RQ1. How do users' cybersickness symptoms and sense of enjoyment vary with the way the wheelchair wheels' rotational speeds are processed in the exergame platform?

RQ2. What factors contribute to a good user experience in a VR wheelchair simulator, and how do they relate to the design and implementation of the exergame platform?

RQ3. What are the characteristics of individuals who experience cybersickness in response to the exergame platform, and how do they differ from those who do not experience cybersickness?

The thesis will address these three research questions to explore different aspects of the VR exergame platform designed for wheelchair users.

Firstly, RQ1 aims to investigate the level of discomfort and enjoyment experienced during the testing of the exergame platform. The question will specifically examine how different iterations of the platform influence the user experience. Specifically, the goal is to iterate upon the exergame platform to improve the user experience. Each iteration will process the measured rotational speeds of the wheelchair wheels differently. By assessing the varying degrees of discomfort and enjoyment, valuable insights can be gained into the impact of different processing methods on cybersickness symptoms and overall user satisfaction.

Secondly, RQ2 seeks to identify the factors contributing to a positive user experience within the exergame platform. The investigation delves into the design and implementation aspects of the exergame platform, aiming to determine which factors are crucial in shaping user perceptions, satisfaction, and engagement. Understanding the elements that influence a good user experience will inform the further development and refinement of the exergame platform.

Lastly, RQ3 aims to find the distinguishing characteristics of individuals who experience minimal cybersickness symptoms when testing the exergame platform. By identifying specific traits, this question seeks to provide general guidelines regarding the user profile that may derive greater enjoyment from utilizing the exergame platform for VR applications. These insights can assist in tailoring the device to better suit the needs and preferences of users, ultimately enhancing user satisfaction and adoption rates.

To address these research questions, a series of experiments was conducted using a prototype of the exergame platform. The experiments involved groups of able-bodied participants with varying levels of experience in VR technology, enabling comprehensive evaluations and the acquisition of valuable data to inform the findings.

1.4 Delimitations

This thesis is based on the project work completed December 2022, which involved creating a basic exergame platform for playing games. The project report, which is included with the thesis submission, presents the details of the initial implementation. The thesis builds upon the previous work and focuses on improving the exergame platform's functionality and reliability. Specifically, the work done in this thesis has transformed the initial, almost-functional version of the exergame platform into a more robust and fully functioning system that meets the requirements of a VR wheelchair simulator.

The thesis will focus on the development and evaluation of a proof-of-concept prototype of a VR exergame platform rather than a fully functional commercial product. This delimitation is necessary to limit the scope of the thesis and make it feasible within the available time and resources. By focusing on a prototype, the thesis can assess the feasibility of the technology and identify areas for further development and improvement.

The thesis will only consider an exergame that involve turning and navigation in a virtual environment, and will not investigate other types of VR games or experiences. This delimitation is necessary to ensure that the conducted study is focused and coherent. By limiting the investigation to exergames that involve turning and navigation, it might be possible to identify specific factors that contribute to user comfort and enjoyment in this specific type of VR experience.

The study will only investigate the effects of scaling, filtering, and clamping of the wheels' speeds on the user experience, and will not consider other factors that may affect user comfort or enjoyment in VR. This delimitation is necessary to ensure that the study is focused on a specific set of factors that are relevant to the exergame platform being developed. By focusing on scaling, filtering, and clamping, the study might identify specific parameters that can be adjusted to optimize the user experience in the VR wheelchair simulator. However, it is acknowledged that other factors, such as the visual and auditory design of the game, may also affect user comfort and enjoyment in VR.

1.5 Terminology

This thesis, and particularly chapter 2, will describe and address challenges pertaining to various functionalities within the exergame platform. Therefore, terms have been defined such that it is simpler to understand what part of the platform is being referred to, and what the parts are composed of. The words used to address parts of the exergame platform is shown in the venn diagram of fig. 1.1.

The **wheelchair ergometer** is the pad/platform which lets the user roll the wheels of their wheelchair in place. It only deals with mechanics and contains no electronics.

The **bridge** refers to the electronics that make it possible to collect data from the ergometer and communicate the data to the VR headset.

The **game controller** consists of the wheelchair ergometer and the bridge. The game controller may also be referred to as ”the device”. The game controller encompasses most of the implementational work done in this thesis. The creation of the best possible game controller is what this project is mostly about, as the game controller and its constituent parts are easily modified.

The **VR headset** refers to the goggles that the user will use to immerse themselves in a virtual world. It is capable of taking input and running games, but is proprietary and very complex, which is why it will be left untampered with.

Finally, the **exergame platform** is the whole system. It is what lets the user immerse themselves in a virtual reality, and will mostly be referred to when talking about user experience. The exergame platform is the combination of the VR headset and the game controller.

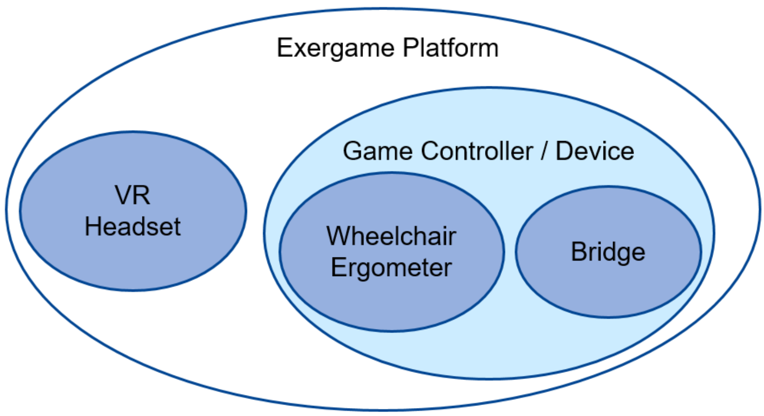


Figure 1.1: Venn diagram of terms used to describe the exergame platform

1.6 Structure of the Thesis

This thesis is structured to provide a comprehensive understanding of the research work conducted. It documents the design choices made throughout the thesis work and the reasons behind them. Chapter 2 describes the final design of the hardware and software for the proposed exergame platform, but recall that most of the in-depth details of the system are given in the attached project report from December 2022. Chapter 3 covers the data collection process, including what data was collected, how it was collected, and why it was collected. The collected data is analysed in chapter 4, where the research questions are addressed. The results from the data analysis are summarized in chapter 5, followed by a discussion of the methodological considerations as well as further work in chapter 6.

Finally, the thesis concludes with chapter 7, which briefly summarizes the main findings and conclusions of the research.

Each chapter's introduction will provide a road map for its contents. Where applicable, the introduction might also briefly summarize the contents of the chapter. Sections and subsections offer further details for interested readers. The thesis is organized in a top-down structure where it's feasible to do so. By providing introductions at the beginning of each chapter and detailed subsections, the report allows readers to gain a general understanding of the thesis work by reading the introductions, and a more specific understanding of the work done by reading the subsections.

This thesis aims to provide a comprehensive understanding of the research topic. By giving clear explanations of the device, research methodology and experimental design, the reader should be left with few questions about the contents of the thesis. The results are analyzed and discussed in detail, allowing readers to grasp the implications of the findings. The thesis aims to provide interested readers, particularly other students, with a good starting point for their own research. The reader will hopefully find it as a reliable resource, providing a strong foundation for further investigations in the field.

2

System Description

The exergame platform is a comprehensive system that provides everything a wheelchair user requires to participate in a VR game, including the wheelchair ergometer, bridge, and VR headset, as depicted in fig. 2.1. A demo of how the exergame platform works can be seen in the public GitHub repository that has been made for this project [22]. Since the VR headset is a ready-made product, this chapter primarily focuses on the implementation of the game controller itself, describing the physical and electronic components in section 2.1, followed by a description in section 2.2 of the user manual that has been developed for the device. This is followed by a description of how the wheelchair was modeled so that the in-game avatar feels realistic in section 2.3. The encoder signals needed to be filtered in order to improve the user experience and is described in section 2.4. An explanation of how and why the output from the bridge is made to fit into the 0-255 range is given in section 2.5. The chapter concludes with an explanation of how the game handles the signal sent from the bridge in section 2.6.

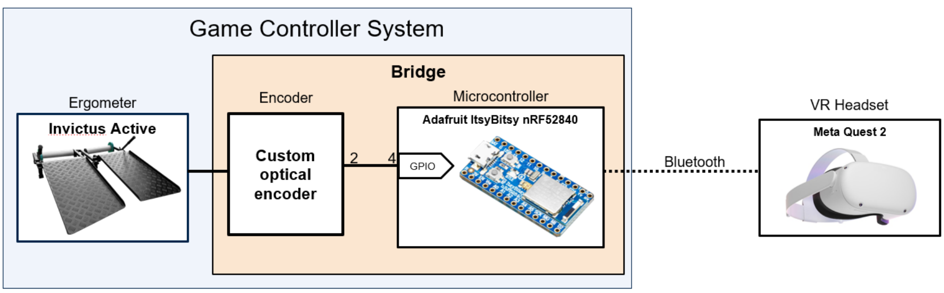


Figure 2.1: Hardware components of the system

2.1 Game Controller

In this section, the implementation work on the game controller is described. The device is referred to as a game controller due to its emulation of a gamepad, thereby convincing the computer or VR headset that it functions similarly to an Xbox or Playstation controller. This is described in section 2.1.3. It is important to note that the project report attached to this thesis provides a comprehensive description of the exact implementation details. Therefore, this section only provides a high-level overview and a summary of the changes to the design implemented in the project report. The game controller is responsible for generating user input from mechanical movement by reading the rotational speeds of the rollers, which is used as the input to the game itself. The game controller, which is shown in fig. 2.2 encompasses the ergometer, encoders and a microcontroller.

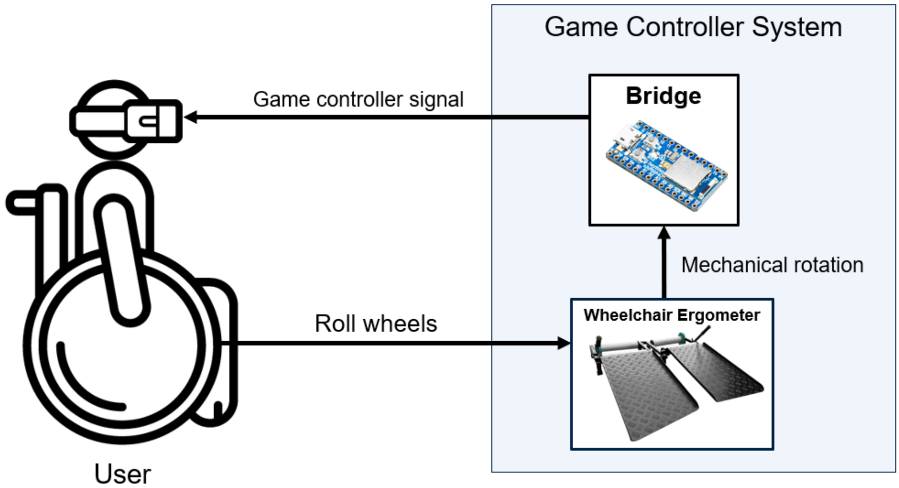


Figure 2.2: Uses and main components of the system

2.1.1 Mechanics

The wheelchair ergometer that has been used is the Invictus Active Trainer, shown in fig. 2.3. Fully reversible modifications were done to this ergometer in order to interface it with a computer or a VR headset. These modifications are described in the following paragraphs.

To calculate the rotational speed of the wheelchair wheels, the rotational speed of the ergometer rollers were measured. Recall from fig. 2.1 that this was done by using two custom optical encoders. These optical encoders were realized by using line sensors (further explained in section 2.1.2) which needed to be placed *very* close to the rollers. Because of this, additional hardware needed to be designed and manufactured such that the line sensors may be placed with millimeter distance from the ergometer rollers. This design is shown in fig. 2.4.

Figure 2.3: The Invictus Active Trainer

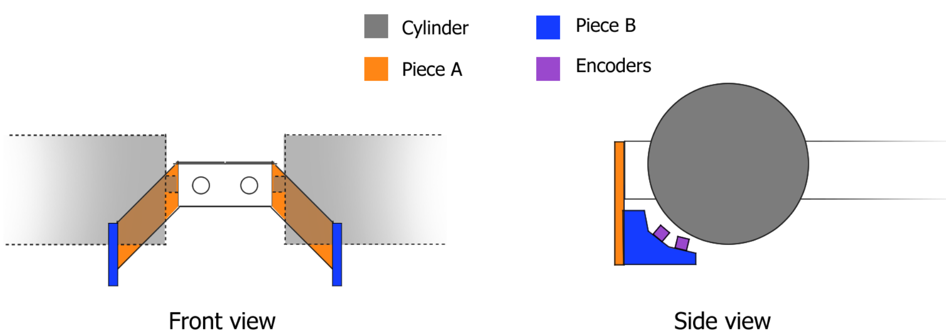


Figure 2.4: Line sensor mounting

In the fall project work, the encoder mounting in fig. 2.4 was manufactured by creating a metal cutout. To make the design more accessible, the encoder mounting was redesigned to be suitable for 3D printing. The design for the mounting was created with the help of the engineers working at the cybernetic department's workshop, and the 3D printable files have been included in the "3D-printable files" folder of the zip attachment. This way, anyone with access to a 3D printer would be able to set up the ergometer in the way that has been done in this thesis. More on the accessibility of the device is described in section 2.2. An enclosure for the electronics was also created, and the whole setup can be seen in fig. 2.5. For further details about precisely how the device is set up, refer to appendix A.

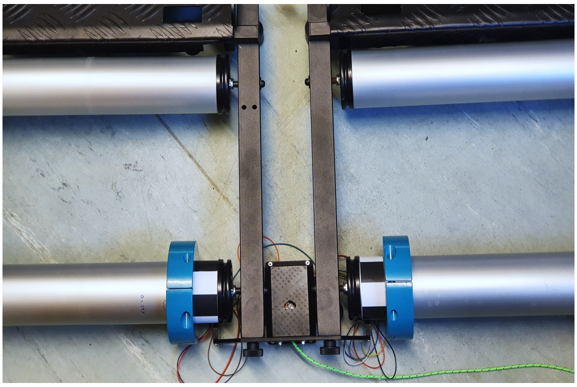


Figure 2.5: Picture of mounted bridge

2.1.2 Electronics

The components used in the bridge were chosen as part of the fall's project work. In short, the bridge runs on the Adafruit ItsyBitsy nRF52840 board, with custom optical encoders having been designed by using two QRE1113, which is a reflective object sensor, for each encoder. This is shown in fig. 2.6. QRE1113 sensors were mounted on ready-made breakout boards by SparkFun, whose module name is ROB-09454. All in all, the system from the project work uses four ROB-09454 and one Adafruit ItsyBitsy nRF52840 to realize the bridge.

A couple of new parts of the electronics circuit were introduced. Specifically, operational amplifiers (op-amps) have been introduced as voltage followers. Using op-amps also required the setup of external pull-ups as the ROB-09454 is active low and requires a pull-up resistor to output a logical high signal. This is shown in fig. 2.7. The reasoning for introducing these changes is further elaborated upon in the following paragraphs.

Adding ESD protection

When testing the system for longer periods of time, for example for 10 or 15 minutes, an unknown event would cause a GPIO pin of the ItsyBitsy to become permanently damaged.

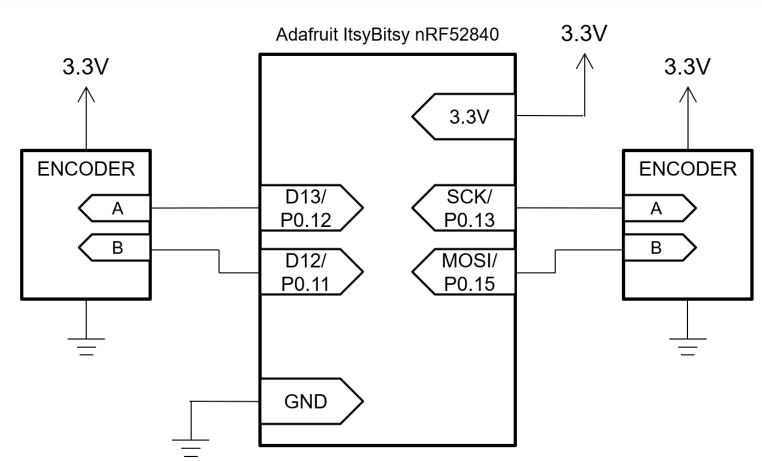


Figure 2.6: Schematic for the bridge

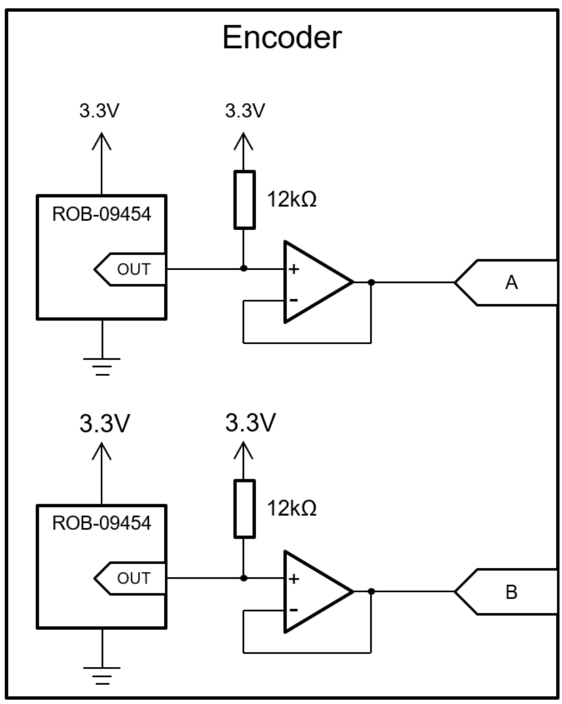


Figure 2.7: Schematic for the encoder

This happened multiple times. This problem was difficult to troubleshoot as it happened infrequently and seemingly out of the blue.

Multiple approaches were used to solve this issue, such as double checking the configuration of the ItsyBitsy, reading the datasheets of all components carefully and ensuring that all the GPIO pins were set up correctly. Additionally, outputs from the ROB-09454 were measured using an oscilloscope. After ruling out all other potential sources of the issue, the only logical explanation was that the damage to the GPIO pins of the ItsyBitsy was caused by electrostatic discharges (ESD).

To counter the ESD problem, voltage-following op-amps were installed at the outputs of the ROB-09454 components. The component that was used was the MCP602, which features ESD protection on all pins [23]. The circuit inside each encoder unit is shown in fig. 2.7. The ROB-09454 requires a pull-up to output a logical high signal. When implementing the op-amp, this meant that the internal pull-up of the nRF52840 to be changed to an external pull-up of 12kΩ.

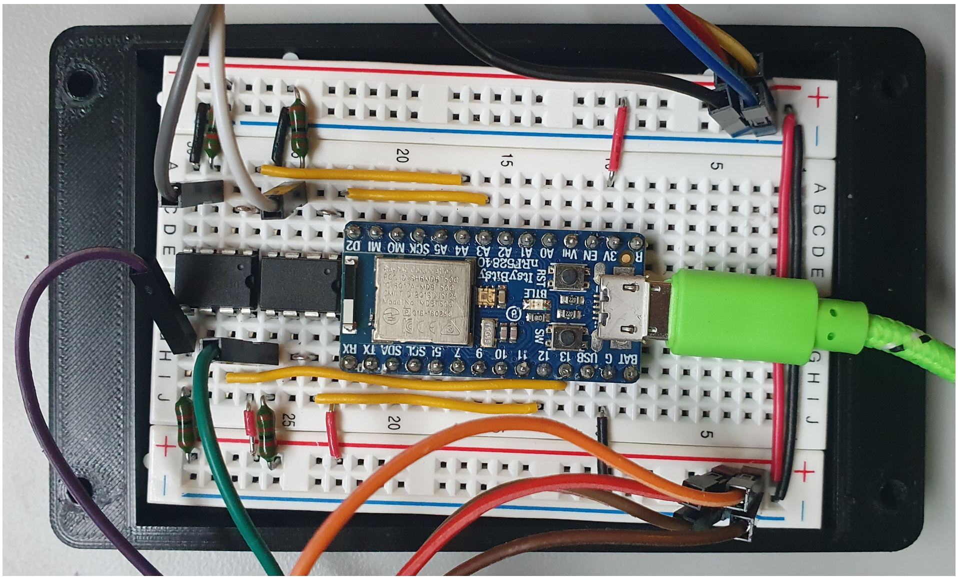


Figure 2.8: Breadboard wiring for the bridge

2.1.3 Software

The software of the game controller is the code that is inside of the microcontroller, the Adafruit ItsyBitsy nRF52840. Note that due to its low-level nature, the code written for the ItsyBitsy is by some considered to be firmware, but in this thesis it is referred to as software. The code that has been implemented, along with a thorough documentation and explanation of how to build the software, is included in the ”Bridge Software” folder of the zip delivered alongside the thesis. The software encompasses all the code needed to convert 0s and 1s from the encoder readings into a meaningful signal. This signal is then converted into a game controller signal before it is transmitted to the VR headset or a computer.

The logical modules implemented in the bridge is shown in fig. 2.9. The encoder module is responsible for sampling the rotational travel for both of the wheelchair wheels and converting it into rotational speeds. The Human Interface Device (HID) module converts the rotational speeds into game controller signals. The LED module informs the user about the state of the device through the blinking of an RGB LED. Finally, the Bluetooth Transmitter module is responsible for everything connectivity related, such as device pairing, connecting and message transmission.

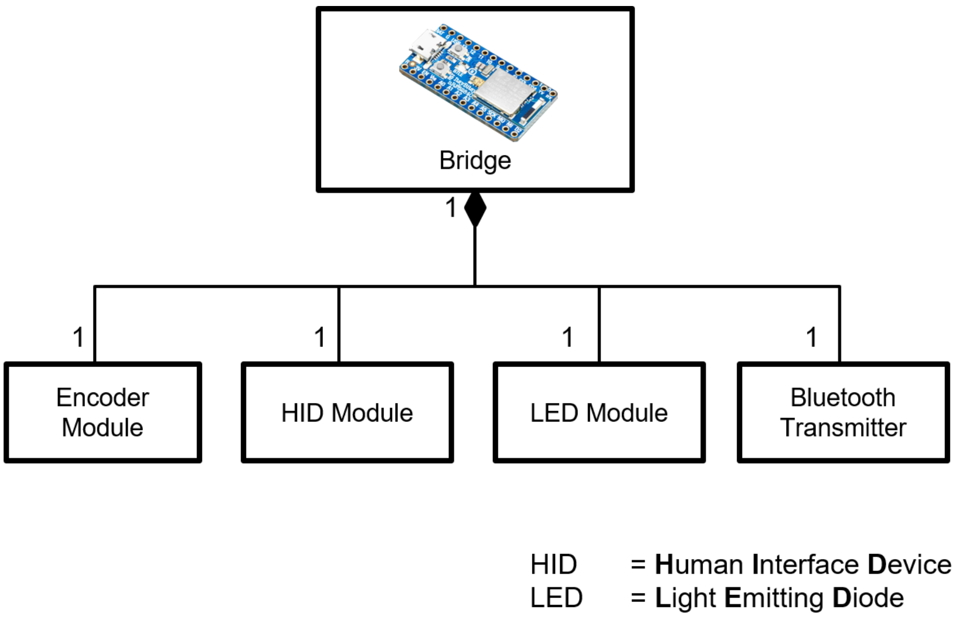


Figure 2.9: Software units in the bridge

The transformation from encoder reading to the bytes transmitted over Bluetooth is shown in fig. 2.10. A software driver for the encoder (the entry point to the bridge) is responsible for converting an encoder line’s transition from 0 or 1 into a rotational signal, in degrees. There are two rotational displacement values, one for the left and one for the right wheel. The encoder module reads the rotational displacement periodically and converts it into a rotational velocity signal. The velocity signals are converted into ”wheelchair speed” and ”wheelchair turning rate” which is explained in section 2.3. The speed and turn rate signals are then filtered, which is further explained in section 2.4. Prior to transmission, the filtered values are converted to fit the Human Interface Device (HID) standard which is explained thoroughly in section 2.5. An explanation of why and how the filtered values are converted to fit the HID standard follows.

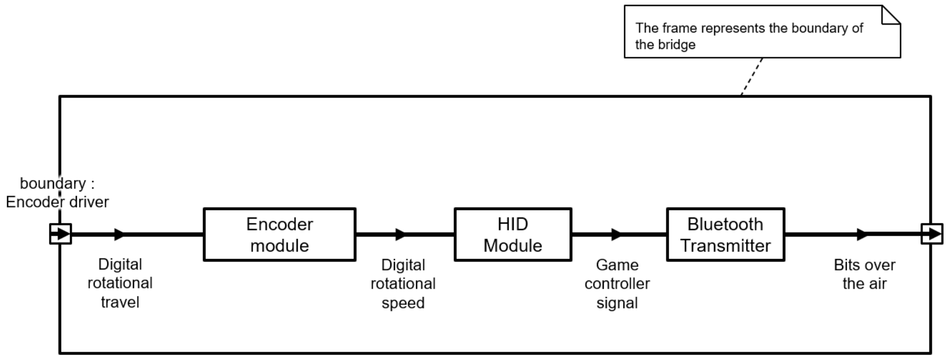


Figure 2.10: Signal flow in bridge

Human Interface Device Emulation

To make it possible to play a wide variety of games on the platform, the game controller system is made to emulate a typical game controller. This way, it is possible to connect the game controller to any game that also supports game pads like the ones created by Xbox or Playstation. This will in practice work for any game, both VR and non-VR. Another benefit of this is that no additional driver installation is required by the VR headset or the PC, as the Human Interface Device (HID) standard is supported on most modern operating systems.

When a HID-compliant device is first connected to a host (a PC or a VR headset), the device sends a series of descriptors to the host. A descriptor is a data structure that provides information about the characteristics and capabilities of the device. Most interesting is the HID report descriptor, which describes the format and contents of the HID reports that the device will send.

The exact implementation of the HID device emulation is more thoroughly explained in the attached project report, but know that the report descriptor implemented for this device describes the data array shown in fig. 2.11. The first two bytes of the report contain 16 bits dedicated to button presses. These buttons are not in use and were implemented mainly due to the fact that many games will not recognize generic game controllers that have less than 16 buttons and 2 joysticks. The remaining bytes in one transmission contain information about the joysticks which in a game typically corresponds to moving the player character.

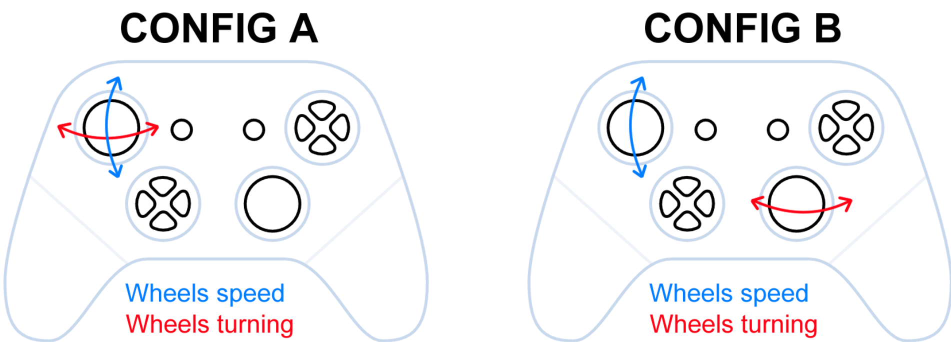
A drawback of the currently implemented HID functionality is that the resolution of the signals are limited to 255 discrete values. For high-precision purposes, this might be

Byte		Notes
0	buttons[0]	8 button bits
1	buttons[1]	8 button bits
2	Left joystick x-axis	
3	Left joystick y-axis	
4	Right joystick x-axis	
5	Right joystick y-axis	

Figure 2.11: Bytes transmitted in the HID report

limiting, but for the purpose of the exergame platform, this was deemed to be sufficient. The trade-off between the maximum expressed signals and the size of the quantization intervals is explored in section 2.5

Two configurations for game pad emulation was implemented. This was done to be able to play different kinds games, based on how the game takes its input. These configurations are shown in fig. 2.12. Config A is the configuration that was used in the study conducted in this thesis.



(a) Config A **(b)** Config B

Figure 2.12: Gamepad configurations

RGB LED

As outlined in in section 1.4, minimal attention was paid to the user experience outside of the actual gameplay. One functionality that proved easy and fast to implement, however, was to use the on-board RGB LED to indicate the state of the game controller system.

By implementing LED functionality, it became easier to tell which state the game controller was in without reading logging output from a serial terminal. The meaning of the implemented colors, blinks and durations is shown in table 2.1.

Color	Number of times	Duration	Meaning
Green	1	Long	The device successfully booted
Blue	1-10	Long	The device is advertising itself as ”Wheelchair Ergometer”. It should be found when you scan for it.
Orange	2	Medium	The device is connected but the connection is not secure.
Green	2	Medium	The device is connected and the connection is secure
Red	5	Short	The device failed to connect to its peer
Red	2	Short	The device was disconnected from its peer

Table 2.1: Light meaning for ItsyBitsy

2.2 Setup Tutorial

As was explained in section 2.1.1, measures were taken to make this technology more accessible. If the work conducted in this thesis turned out to be successful, then it would be greatly beneficial to make the project accessible through making it open-source. This way, anyone that owned an Invictus Active Trainer would be able to make the necessary adjustments to interface the ergometer with a game.

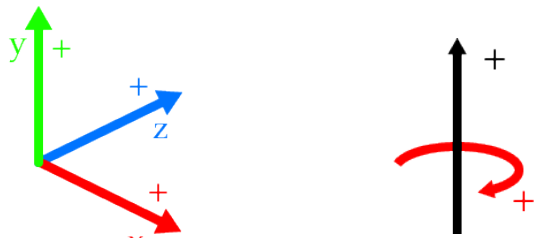
The open-source approach fosters collaborative contributions, which might enhance the platform’s capabilities and broadening its reach. By investing in a comprehensive documentation and user-friendly guides, a more inclusive, accessible and innovative technological landscape may be created for potential users and developers alike.

The documentation for setting up and using the device has been included in appendix A. This manual provides a structured guide to implementing and using the exergame platform effectively. The project has been made public on under the GitHub repository ”wheelchair-ergometer-game-controller” under the MIT License [22].

2.3 Modeling the Wheelchair

The goal is to have the wheelchair moving around in VR feel as realistic as possible. The best way of achieving a realistic movement is by modeling the physics of the wheelchair. This section addresses the key problem of "how does the rotation of the wheelchair wheels affect the user's orientation and position?"

The coordinate system used in this section are shown in fig. 2.13. Due to the game engine's coordinate system being left-handed, the coordinate system for this section was also chosen to be left-handed.



(a) Axes definition

(b) Positive rotational direction

Figure 2.13: Left-handed coordinate system

2.3.1 Position and Rotation for the In-Game Model

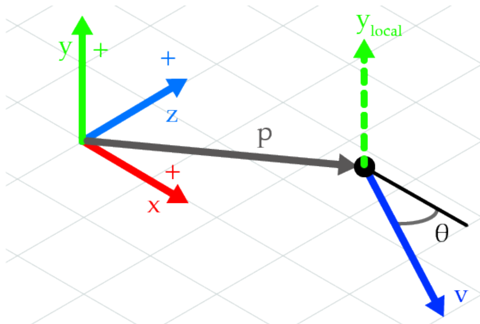


Figure 2.14: In-game position and velocity

The VR game is in a first person view and mainly gives feedback to the user through a change in the player's position and orientation based on the user's input to the system. The player's position $\mathbf{p}$ and and rotation θ are shown in fig. 2.14. A more thorough explanation of these two quantities follows.

The in-game position $\mathbf{p}$ of the player is simply stated and given in eq. (2.1). To simplify the model, the y-value of the position is locked to a constant value.

$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \end{bmatrix} \tag{2.1}$$

The player's orientation in the game is the result of a composite rotation first about the local z-axis, then about the local y-axis and finally about the local x-axis. This operation is given by eq. (2.2)

$$\mathbf{R}(\phi, \theta, \psi) = \mathbf{R}_x(\phi)\mathbf{R}_y(\theta)\mathbf{R}_z(\psi) \tag{2.2}$$

The game has no slopes, and the player is locked to a constant position on the vertical axis. This means that there is no reason to rotate the player about the z-axis. There is also no instance in which the player will be rotated about the x-axis. As such, the only rotations that will take place will be about the y-axis, meaning $\phi, \psi = 0$. This results in eq. (2.3), which when combined with eq. (2.4) yields eq. (2.5).

$$\mathbf{R}(0, \theta, 0) = \mathbf{R}_y(\theta) \tag{2.3}$$

$$\mathbf{R}_y(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{2.4}$$

$$\mathbf{R}(\theta) = \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \tag{2.5}$$

The update of the transformations on the in-game character, or camera, in eqs. (2.3) and (2.5) is how the player experiences feedback in the game. The updates of these equations are derived and explained in section 2.3.2.

2.3.2 Equations of Motion for the In-Game Model

This section describes how the input to the game results in the world space velocity of the player. The velocity is applied to the player's position each frame. The section describes some simplifications done to the in-game modeling of the wheelchair and is meant to give the reader an idea of how the in-game movement works.

Figure 2.15 shows the input to the game, namely the velocity $\mathbf{v}$ and the angular velocity about the local y-axis, ω. In the game engine, the velocity is given in world coordinates whereas the angular velocity input is given about the object's local y-axis.

The value Δt is used in the update eqs. (2.6) and (2.7) and represents the elapsed time between the current and the previous frame. This interval varies based on the hardware of the PC and the amount of resources made available to the game. Normally, the target frame rate is 120FPS, which means that the expected value is $\Delta t \approx 8.3$ msec.

Let ω be the angular velocity about the object's y-axis. The player's rotation about the y-axis, θ, is updated according to eq. (2.6). The in-game units are given in degrees.

$$\theta[t] = \theta[t-1] + \omega[t] \cdot \Delta t \tag{2.6}$$

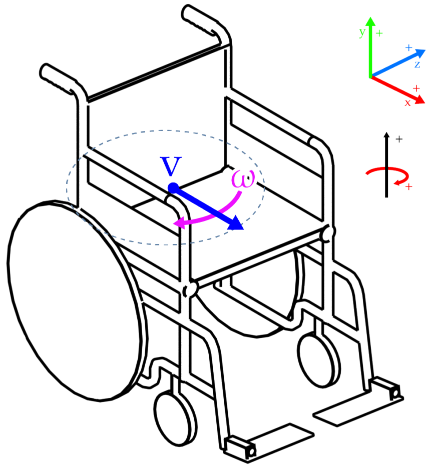


Figure 2.15: Input to the in-game model

The position of the player is updated each frame and is updated by eq. (2.7). The in-game position is such that 1 in-game unit is approximately the same as 0.5 meters.

$$\mathbf{p}[t] = \mathbf{p}[t-1] + \mathbf{v} \cdot \Delta t \tag{2.7}$$

Recall that the player is locked to a single vertical position in-game. That is, the y-component of the position remains constant. The world-space velocity of the player may then be defined as in eq. (2.8).

$$\mathbf{v} = \begin{bmatrix} v_x \\ 0 \\ v_z \end{bmatrix} \tag{2.8}$$

Whereas the angular velocity may be used as a direct input to the players's orientation, the velocity $\mathbf{v}$ must be calculated based on the player's orientation. The simplest way to derive the player's velocity is by first finding it in local space, then converting this to world space. These two reference frames, world space coordinates and local space coordinates are shown in fig. 2.16.

Local Space

A wheelchair is constrained to moving forwards or backwards in a straight line. In-game, this axis corresponds to the x-axis in the object's local coordinate system. Notice that the dotted line x_{local} aligns with v in fig. 2.16. By converting the world-space velocity given in eq. (2.8) to local space, the velocity is simplified to eq. (2.9).

$$\mathbf{v}_{local} = \begin{bmatrix} v_{lx} \\ 0 \\ 0 \end{bmatrix} \tag{2.9}$$

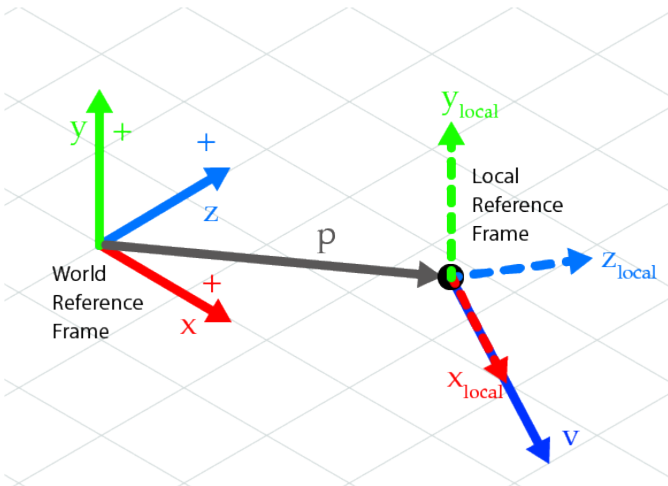


Figure 2.16: Global and local reference frames

World Space Velocity

The velocity of the player given in world coordinates is influenced by the direction in which the player is facing. The direction the player is facing is determined by eq. (2.3). As a result, the velocity of the player in world coordinates will be determined by eq. (2.10).

$$\mathbf{v}_{world} = \mathbf{R}(\theta)\mathbf{v}_{local} \tag{2.10}$$

2.3.3 Game Inputs from Roller Speeds

As mentioned in section 2.3.2, the input to the game is the wheelchair's velocity $\mathbf{v}$ and its rotational speed, ω. This section addresses how these values may be derived from the measured rotational speeds of the rollers on the ergometer. To calculate these values, additional quantities are introduced which are defined in the box (2.11). Since additional linear and angular velocity variables are introduced, $\mathbf{v}$ and ω have been renamed to v_p and ω_p for the sake of clarity. ω_p is used as an input to the equation eq. (2.6). v_p is given to the game in local space like eq. (2.9). In the game, this value is transformed to world space as was done in eq. (2.10).

Descriptions of variables

$$\begin{aligned} v_p &: \text{The instantaneous translational speed of the player} \\ \omega_p &: \text{The instantaneous rate at which the player turns} \\ \omega_A &: \text{The measured angular velocity of pipe A} \\ \omega_B &: \text{The measured angular velocity of pipe B} \end{aligned} \tag{2.11}$$

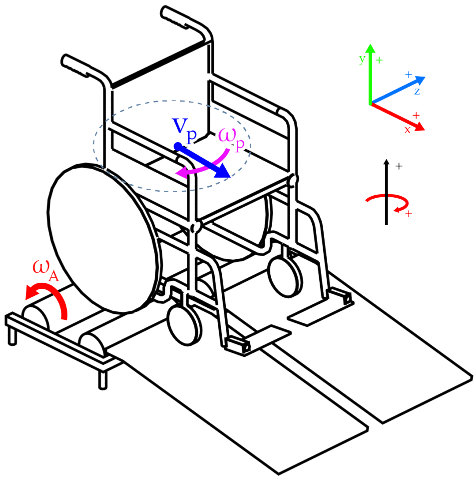


Figure 2.17: Problem description for modeling the wheelchair

Using fig. 2.17 as a reference, the problem can be posed as follows: Given the measured rotational speeds of the ergometer's left roller ω_a and its right roller ω_b, find the in-game translational speed v_p and the angular velocity ω_p of the player.

Model assumptions:

- There is no slipping between the wheelchair wheels and the cylinders
- In-game, the wheels do not slip
- The friction between the in-game wheelchair wheels and the game world is as high as the friction between the wheels and the rollers

For this model, the linear velocity and angular velocity is only influenced by the movement of the wheels. Figure 2.18 shows a top-down view of the wheelchair with the translational velocities of each wheel, v_A and v_B, as well as the radius from the player's origin to each wheel, r_p. For the sake of clarity, the extra quantities are also shown in fig. 2.19. The player's velocity along the local x-axis, v_p is given by the sum of the two linear velocities in eq. (2.12).

$$v_p = v_A + v_B \tag{2.12}$$

The turning rate of the player, ω_p, is given by the sum of the angular velocity contributions from each wheel. This is shown in eq. (2.13). The subtraction follows from the fact that the contribution from v_A is pointing in the counterclockwise direction, which in a left-handed coordinate system is the negative direction.

$$\omega_p = \omega_{bp} - \omega_{ap} \tag{2.13}$$

The quantities ω_{ap} and ω_{bp} denote the angular velocity contributions from the two wheels on the player's turning rate and are calculated through eqs. (2.14) and (2.15)

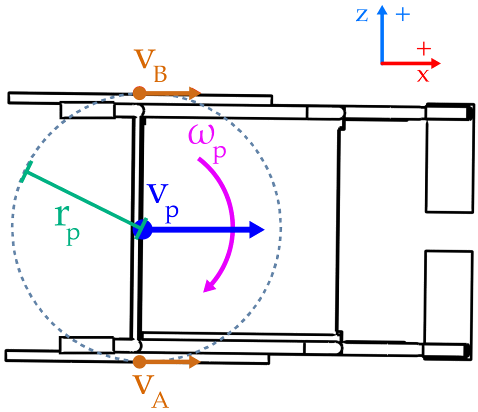


Figure 2.18: Top-down view of the problem

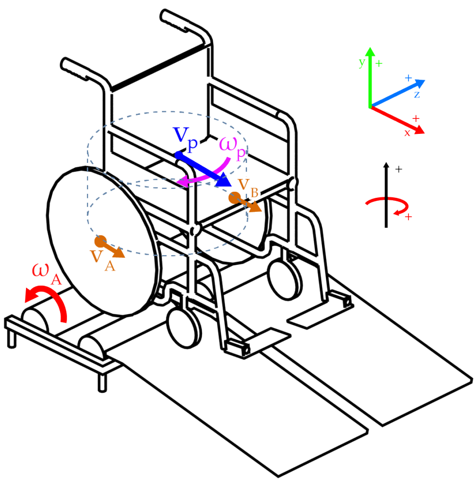


Figure 2.19: Annotation of intermediate quantities

$$\omega_{ap} = \frac{v_A}{r_p} \tag{2.14}$$

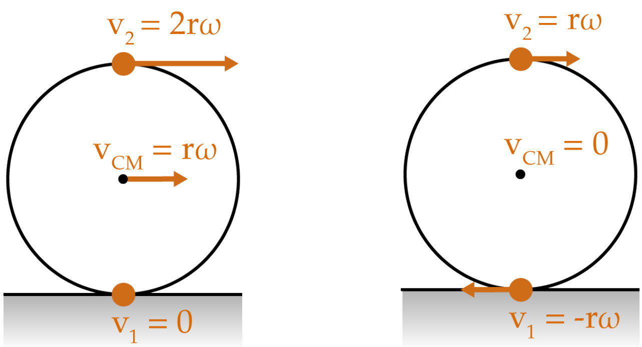
$$\omega_{bp} = \frac{v_B}{r_p} \tag{2.15}$$

Combining eq. (2.13) with eqs. (2.14) and (2.15) gives the relationship between ω_p and the translational velocity of the right wheel v_A and left wheel v_B. This relation is shown in eq. (2.16).

$$\omega_p = \frac{v_B - v_A}{r_p} \tag{2.16}$$

From Pure Rolling to Rolling without Slipping

Under normal circumstances, a wheelchair moves by the rolling motion of its wheels. This movement can be modeled as rolling without slipping, shown in fig. 2.20a. For rolling without slipping, the translational velocity of the wheel's center (v_{CM} in fig. 2.20a) is given by the radius of the wheel multiplied by its angular velocity. That is, $v_{CM} = r\omega$.



(a) Rolling without slipping (when on the ground)

(b) Pure rolling (when on the trainer)

Figure 2.20: Rolling motion with and without slipping

When the wheelchair is placed on the ergometer, the wheels exhibit pure rolling behaviour. The wheels will spin in place, which means that $v_{CM} = 0$. The measured rotational speeds of the rollers can be used to simulate the movement of the wheelchair in a virtual environment. The same calculations are applied as if the wheelchair was moving normally, even though it's simply spinning in place. That is, the wheelchair in the game rolls as in fig. 2.20a but the real-life wheelchair rolls as in fig. 2.20b.

The velocity vectors v_A and v_B may be determined by measuring the angular velocities of the rollers. The relationship between a roller's angular velocity and the magnitude of the forwards velocities in the case of rolling without slipping is shown in eqs. (2.17) and (2.18). v_{AC} and v_{BC} is the tangential velocity of both the wheel and the roller at their contact point. The equations are derived from fig. 2.21.

$$|v_A| = |v_{AC}| = r_c \cdot \omega_A \tag{2.17}$$
$$|v_B| = |v_{BC}| = r_c \cdot \omega_B \tag{2.18}$$

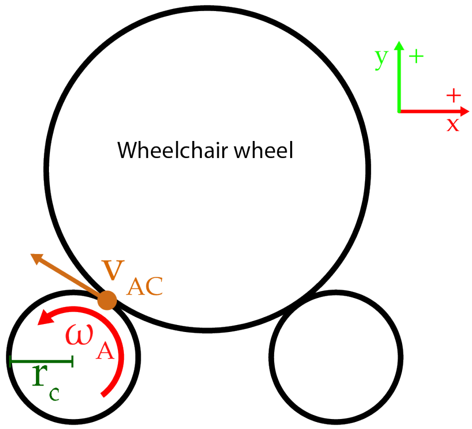


Figure 2.21: Instantaneous tangential velocity of one wheel

Putting It All Together

Combining eqs. (2.12) and (2.16) with eqs. (2.17) and (2.18) yields eqs. (2.19) and (2.20). With this, the inputs to the game in terms of the measured roller speeds have been found.

$$\omega_p = \frac{r_c \cdot (\omega_b - \omega_a)}{r_p} \tag{2.19}$$
$$v_p = r_c(\omega_a + \omega_b) \tag{2.20}$$

These are more or less the quantities that are transmitted from the bridge to the VR Headset. Specifically, the values are very close to the quantities referred to as ”Wheels speed” (v_p) and ”Wheels turning” (ω_p) in fig. 2.12. The reason they are not *exactly* the quantities that are transmitted is due to some additional processing, filtering and smoothing that is applied to the quantities prior to transmission. This is further explained in sections 2.4 and 2.5.

2.4 Signal Processing

This section describes the various filtering steps done on the sampled rotational speeds of the rollers. Some of the filtering steps have been changed between device versions. This section as well as section 2.5 describes the main mechanisms that have been the object of change throughout the various device iterations. This section starts out with an overview before going into deeper detail of the various filtering steps.

The pipeline that turns the encoders' 0s and 1s into the player input is illustrated in fig. 2.22. The signal is sampled as described in section 2.1.3, and the rotational speeds of each roller is calculated as in the comment box C2 of fig. 2.22. The rotational speeds for each roller is then filtered using an IIR filter, shown in C3 of fig. 2.22 and further described in section 2.4.1. From the filtered angular velocities of the rollers, the angular and linear velocities of the player is calculated. This was explained in section 2.3 and the formulas used are shown in C4.

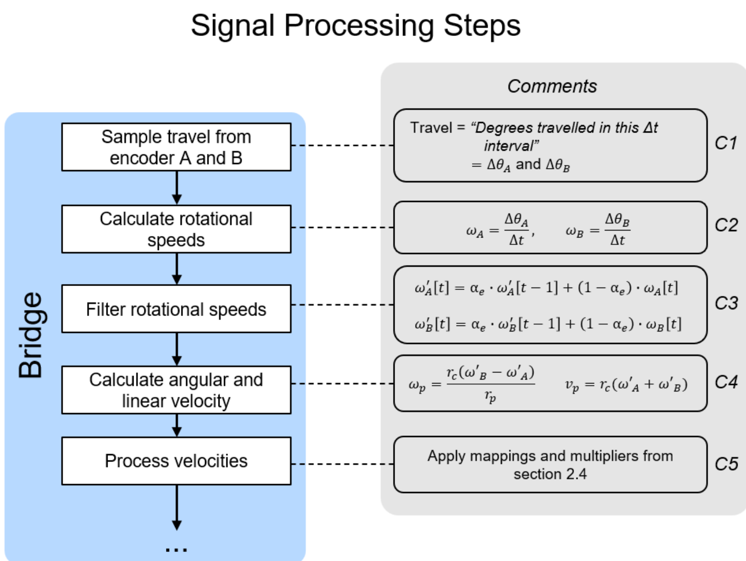


Figure 2.22: Signal Processing Steps

The mathematical operations performed during the "Process velocities" step of the pipeline are summarized in eq. (2.21). First, the turn rate signal ω_p is scaled down by a factor of s which is further described in section 2.4.2. Then, a mapping function f is applied to the signal. The two different mapping functions, *linear* and *slow start*, are described in section 2.4.3. Finally, the turn rate is scaled down by a factor of m, which depends on the forwards speed v_p of the wheelchair and is described in section 2.4.4.

$$\omega'_p = m \cdot f(s \cdot \omega_p) \tag{2.21}$$

m : turn signal reducer, $\{m \in \mathbb{R} | 0 \leq m \leq 1\}$
f : mapping function *(linear or slow start)*
s : turn rate scaling *(constant)*, $\{s \in \mathbb{R} | 0 \leq s \leq 1\}$
ω_p : Calculated turn rate

2.4.1 Infinite Impulse Response Filter for Encoder Samples

Early testing found that the encoder readings might be experienced as ”jagged” or ”choppy” if the raw output was used. This might be because the rotational speed is found by dividing the difference in rotational travel by the sampling interval as shown in eq. (2.22). The sampling interval was chosen to be $\Delta t = 0.05s$ and so dividing by this value makes ω somewhat erratic.

$$\omega[t] = \frac{\theta[t] - \theta[t-1]}{\Delta t} \tag{2.22}$$

A first order infinite impulse response (IIR) filter was implemented as shown in eq. (2.23). This filter was implemented for each roller side, meaning the smoothing was done on both ω_A and ω_B from section 2.3.

$$y[t] = \alpha y[t-1] + (1-\alpha)x[t] \tag{2.23}$$

$$\begin{aligned} y[t] &: \text{output value, initialized to } 0 \\ x[t] &: \omega[t],\ \text{rotational speed of one roller} \\ \alpha &: \text{Coefficient} \end{aligned}$$

Figure 2.24 shows the result of filtering the sequence from fig. 2.23 with various α coefficients. The first order IIR filter leads to a greater smoothing for greater values of α. During early testing, different α values were tested and it was found that $\alpha = 0.7$ proved an adequate balance of smoothing and responsiveness.

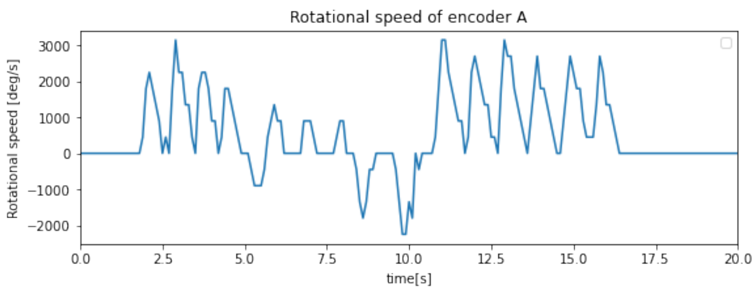


Figure 2.23: Encoder readings without filtering

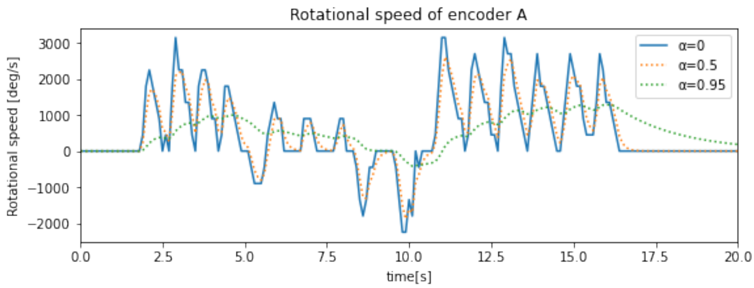


Figure 2.24: Encoder readings with various IIR filter alphas

2.4.2 Turn Rate Scaling

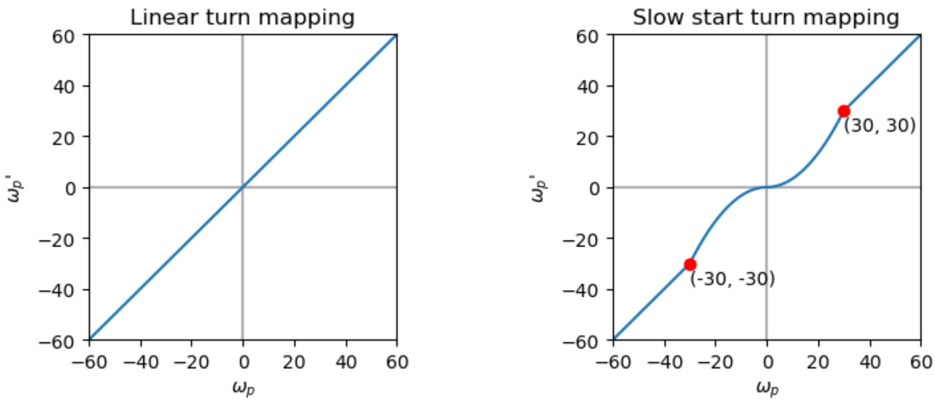
In early iterations of the device, the turn rate was not scaled. After a lot of testing, it was found that using the calculated turn rate signal ω_p resulted in an in-game turning that felt unrealistically high when used directly. In the final version of the device, a scaling factor of 0.25 was used. After having double checked the model, physical measurements and code implementation, there was no clear reason as to why this is seems to work better than the expected values.

No matter the reason, the turn rate had to be scaled down in order for users to get a sense of control. This constant turn rate scaling factor was introduced as s in eq. (2.21). The scaling factor was found experimentally together with the clamping values. The process for finding the scaling factor s is closely described in section 2.5.

2.4.3 Turn Mappings

One of the greatest challenges when developing this device was to make sure the in-game avatar only turns when the user intends for it to turn. Based on feedback given by users in the early tests of the device, turning when not meaning to was a great source of discomfort when testing the system. Attention thus had to be paid to ensuring that the in-game avatar *never* turned unless the user intended for the avatar to turn.

In particular, there was the issue of users rarely applying exactly the same force to each wheel. This small difference in rotational speed of the wheels lead to an ever so slight turning signal being sent to the game, which users found unpleasant. As such, different signal mappings were tested. In short, after the linear mapping (fig. 2.25a) was found to be inadequate, the *slow start* mapping (fig. 2.25b) was implemented, which seemed to be less problematic to users. A brief explanation of the mappings follow.



(a) Linear turn signal mapping

(b) Slow start turn mapping

Figure 2.25: Turn mappings

Linear

For the earliest tests run in this thesis, a simple linear mapping of the turning signal was implemented. The signal was not transformed from input to output and is mathematically described in eq. (2.24). The mapping is also illustrated in fig. 2.25a. The linear turn mapping was used in device versions 1 and 2.

$$\omega_p' := f(\omega_p) = \omega_p \tag{2.24}$$

Slow Start

The mapping named *slow start* is shown in fig. 2.25b. Note that ω_p is given in deg/s, not rad/s. Here, output of the mapping $f(\omega_p)$ will act as a 2nd degree polynomial for turning speeds of 0-30 deg/s, and linear for turning speeds larger than 30. The same is true for negative signals. Although the mapping is non-smooth, it is computationally cheap and was found to be adequate during testing. The mathematical relation is shown in eq. (2.25).

$$\omega_p' := f(\omega_p) = \begin{cases} sign(\omega_p) \cdot 30 \cdot \left(\frac{\omega_p}{30}\right)^2 & \text{if } |\omega_p| < 30 \\ \omega_p & \text{if } |\omega_p| \geq 30 \end{cases} \tag{2.25}$$

The slow start mapping alleviated the main problem with the linear mapping where the user would experience that their character turned even if the wheel speeds were just *slightly* unequal. Although some users have claimed that this configuration feels somewhat unresponsive, this is in the context of VR games better than the turning being too responsive.

2.4.4 Varying Turning Sensitivity with Speed

It is safe to assume that if the user applies a rotation to only one wheel while standing still, they want to turn. The more difficult-to-address problem is when they are moving

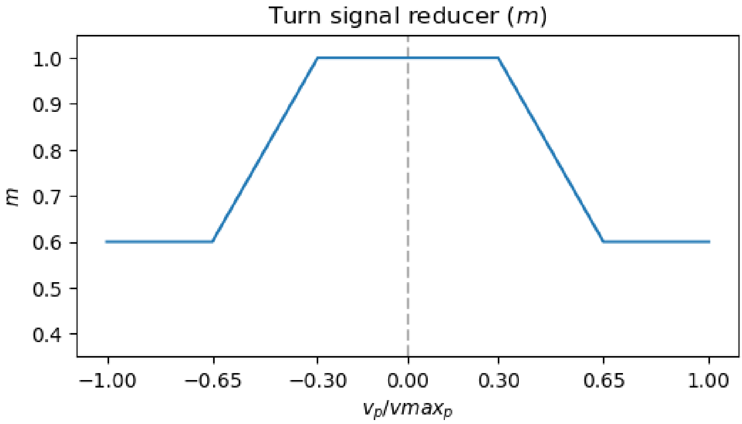


Figure 2.26: Turn signal sensitivity reducer

forwards at a high speed but the force applied to each wheel is slightly different. Does the user want to turn, or are they just not applying the force to each wheel *exactly* the same? Perhaps they want to turn just a little bit?

In the game, users have to push hard on both wheels to achieve higher speeds. During pre-trial testing, it was observed that the turning signal was very large in the case of the user wanting to go fast, but did not push with the exact same amount of force on both wheels. This phenomenon made it difficult for users to control their avatar, particularly during high-speed turns. As such, users moving at high speeds often turned harder than they intended to, leading to confusion and disorientation in users.

This led to the implementation of a multiplier that reduces the turning signal as the forwards signal increases, which is meant to provide a greater sense of control and consistency to the users. In addition to the increased sense of control, this multiplier also added a sense of inertia to the player character which made gameplay overall feel more realistic. Since this multiplier made the control mechanism more intuitive, it is also likely that users will experience a less severe level of cybersickness after playing the game.

The turning reduction multiplier was introduced as m in eq. (2.21) and is shown in fig. 2.26. This exact multiplier has been used in all the versions of the game controller. The equation that determines the multiplier is shown in eq. (2.26). vmax_p is the value at which the linear velocity signal is clamped. In every iteration of the device was set to be $3.5m/s$. The value vmax_p was found experimentally, with the exact approach used to deduce the maximum value being described in section 2.5.

$$m\left(x\right) = \begin{cases} 0.6 & |x| \geq 0.65 \\ -1.14|x| + 1.34 & 0.3 \leq |x| < 0.65 \\ 1 & |x| < 0.3 \end{cases} \tag{2.26}$$

x : $\frac{\mathrm{v}_p}{\mathrm{vmax}_p}$, current speed as a fraction of max speed

2.5 Signal Limiting and Restoration

This section mainly refers to operations that relate to the conversion of the signal from a floating-point value to an unsigned integer in the 0-255 range. For the sake of completion, a description of how the transmitted unsigned integer value is handled on the game side.

Figure 2.27 describes the continuation of the data pipeline introduced in fig. 2.22. After the angular velocity ω'_p and the linear velocity v_p have been calculated, these values must be limited to fit into one byte, or 256 different levels. The byte conversion is done by defining the values vmax_p and $\omega'\text{max}_p$ which are values found in section 2.5.1. How these values affect the user's sense of control is discussed in section 2.5.2. The bytes for v_p and ω'_p are transmitted to a PC or a VR headset. Inside of the game engine, the 0-255 value range is interpreted as a floating-point number in the range $[-1, 1]$. Since the goal is to give the user a realistic experience, this $[-1, 1]$ range must be restored on the host side to reflect the measured angular and linear velocities of the player. This restoration is done on the game side by multiplying the y-axis input with vmax_p and the x-axis input with $\omega'\text{max}_p$.

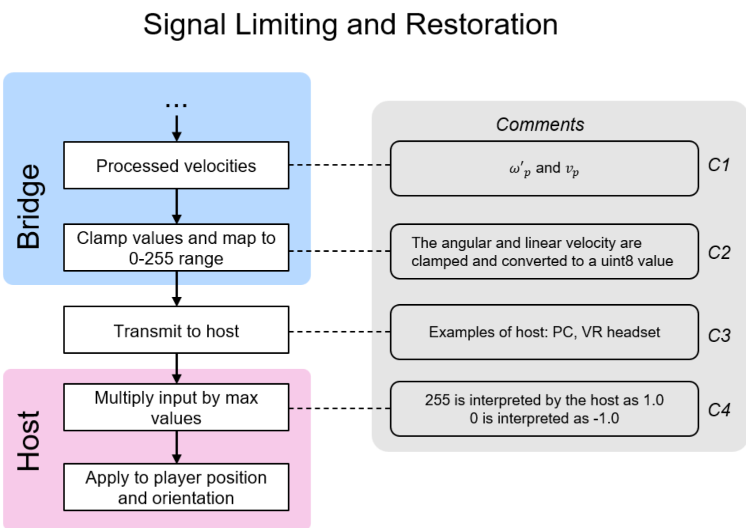


Figure 2.27: Signal Limiting and Restoration, a continuation of fig. 2.22

2.5.1 Choosing Maximum and Minimum Values

Realistic upper and lower bounds for the input quantities, i.e. $\omega'\text{max}_p$ and $v\text{max}_p$, were found by inspecting the inputs v_p and ω'_p from a simple test run. The result of these values were logged and are shown in figs. 2.28 and 2.29. The results for the linear velocity seemed plausible enough given that the sampling intervals are short. In fig. 2.28, the velocities peak in the 4m/s range. The turn rate somehow seemed very high, shown in fig. 2.29, peaking at a magnitude of 600 deg/s.

As described in section 2.5, the signals will be turned into a value in the range of 0-255. The size of the interval between maximum and minimum values will affect the range of floating-point values that are quantized into one number, which is further described in section 2.5.2. For now, know that in order to preserve some granularity of the linear velocity of the player, a clamping value of $\pm 3.5[m/s]$ was chosen. Upon testing, this was found to be sufficient both for granularity and for the user not to clearly feel that the input was clamped. Because of this, the clamping value vmax_p was kept the same throughout all the experiments.

As for the clamping value of the angular velocity, early testing found that $\pm 600[deg/s]$ was too large, as the interval for each byte would become so large that it was possible to notice the shift from one level to the next. Additionally, rotating at such a high rate was very uncomfortable and there was no reason to expect that users would actually want to rotate this fast. A different approach was thus done for choosing the clamping values of the angular velocity: Measure how long it takes to turn a wheelchair $360°$, divide 360 by this time and use that as a max value. Repeated measurements showed that at the fastest, it took 2.5 seconds to turn $360°$ which means that a reasonable value for the turn rate limits were $\omega'\text{max}_p = \pm 150 deg/s$. Choosing and modifying the clamping value for the angular velocity is one of the key differences between the different versions of the device and is described in section 3.6.4.

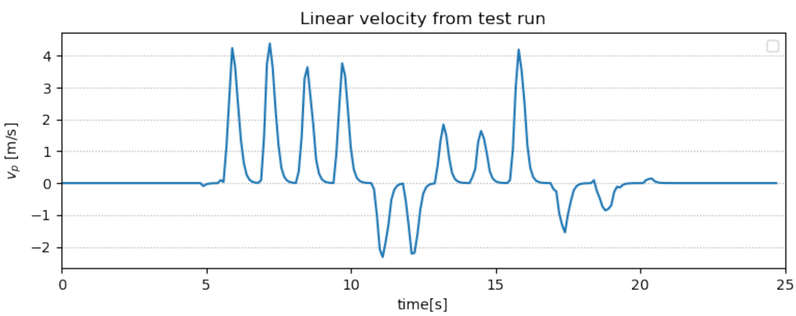


Figure 2.28: Test run: Linear velocity

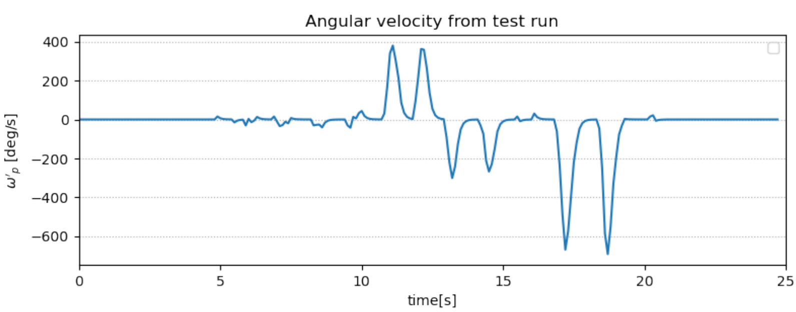


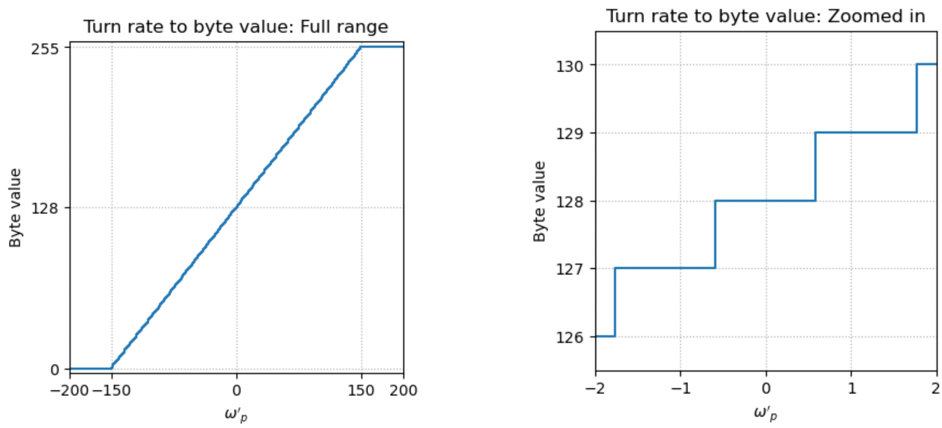
Figure 2.29: Test run: Angular velocity

2.5.2 Quantization of Floating Point Values

As shown in C2 of fig. 2.27, the device's output needs to be converted to an uint8 value prior to transmission. In this standard, the output for each axis on a game controller joystick is limited to 1 byte, meaning the floating point data that is to be transmitted to a host needs to be converted to the range 0-255 where 128 signifies a neutral position, or ”no input”.

For this reason, there is the need to define what values corresponds to 0, and what values correspond to 255. The trade off between the size of the rounding intervals and the maximum values that may be expressed then comes into question. An example of the problem at hand is shown in fig. 2.30, where the full range was set to $[-150, 150]$ for the turning rate. Any value above 150 will map to 255 and any value below -150 maps to 0. As shown in fig. 2.30a, the number 128 covers all rotational speeds in the range $[-0.6, 0.6]$. This interval would be larger if the limits were farther apart than ± 150.

Ensuring that the range is large enough for the user to not feel like their input is clamped, yet small enough that the user cannot feel the shift from one level to the next, was done experimentally. Indeed the clamping value for the angular velocity of the player has been changed from version to version and is detailed in section 3.6.4.



(a) Full range

(b) Zoomed in on $\omega'_p = 0$

Figure 2.30: ω'_p to byte values

2.6 Game

The game which was developed to test the system is a simple walking simulator (or perhaps better put, a rolling simulator). The game was developed using the Unity game engine, specifically Unity 2021.3.13f1. The game files have been included in the ”VR-wheelchair-game” folder of the zip delivered alongside the thesis. The main reason for creating a custom game for this thesis was so that it would be easy to control and change how input was handled, as well as other parts of the game that might need to improve. Additionally, creating a custom game allowed for logging outputs such as the user’s cumulative distance travelled. In other words, developing a custom game gives full control over the whole VR experience that was used for the study.

2.6.1 Gameplay

The gameplay is simple, with the player racing around a track as shown in fig. 2.31. The player competes against themselves to attain the best possible lap time. The visuals consist of simple shapes under a blue, cloudy sky. There are multiple reasons why the game was made to be very bare-bones:

1. Simple visuals has been shown to be less cybersickness-inducing [24].

2. The primary goal is to evaluate the platform as a whole, not to make the most fun/engaging game.

3. Making the game as simple as possible (while still being a gaming experience) allows for spending time on other aspects of the project, such as data analysis.

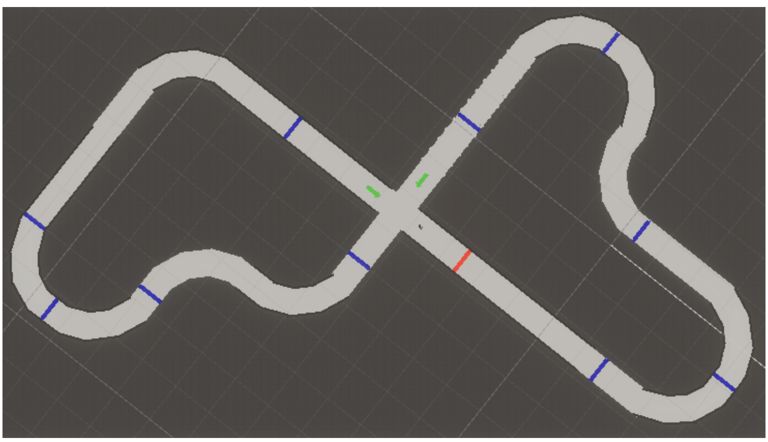


Figure 2.31: Track around which players race

2.6.2 Input Handling

A bit of work needed to be done to figure out how to get Unity to automatically recognize the game controller. This was done using Unity's Input System. This section is brief and uses a lot of new words and concepts directly related to the Unity game engine. The section describes the system that enables one of the key strengths of using Unity, namely that it is possible to test the game at home using a mouse+keyboard or a standard game controller. Since a lot of time was spent setting this up, this section has been included so that particularly interested parties might learn from the approach taken to handling the input.

In the final version of the game, the game recognizes the inputs sent from the bridge by using Unity's Input System, which is a system for processing user input[25]. This allows for the format and handling of input data to be abstracted away, leaving the developer to focus on the gameplay logic. The Input System allows developers to create input actions, which are sets of input bindings that can be triggered by a user's input [26].

Input Bindings provides a way to connect a specific input source, such as a keyboard key or a game controller button, to a specific action in the game or application. In Unity's Input System, an input binding is typically defined as a combination of a control device (such as a keyboard, mouse, or game controller) and a control element (such as a specific key, button, or axis) [26]. An input action might for example be "jump", which might have the input bindings for the space bar on a keyboard or the A button on an Xbox game controller.

One of the key features of the Input System is its ability to handle multiple input devices and platforms seamlessly. Developers can define input actions that work across different platforms and input devices without needing to write platform-specific code. It will as such be easy for a developer to test the game without having access to the ergometer. Indeed, all that is needed to test and iterate upon the game is a computer and a mouse+keyboard. If the game works for the mouse+keyboard inputs, it will work the exact same way when using the ergometer signals as input. This enables developers to create games for the ergometer without ever actually testing the game on the ergometer itself, which is a great strength of using the Input System.

In order to get the ergometer to be recognized and handled correctly, a custom Input System Descriptor had to be made. In short, this is simply a way to tell Unity that "on the ergometer control device, the first received byte is a joystick's x-axis, the second byte is the joystick's y-axis" [27]. Then, an *action map* had to be created for the ergometer device. That is, Unity had to be told that "when using the ergometer control device, the received x-axis values should be handled as a *turn* action, and the y-axis values should be handled as a *move* action".

3

Data Collection

In order to be able to draw any meaningful conclusions about the research questions, data must be collected. Which data to collect? Recall that the research questions aim to assess the cybersickness and enjoyment levels, the user experience of the device as well as the differences between people who become cybersick and not.

A questionnaire was answered by every study participant and is included in appendix F. Additionally, sensor values such as users' heart rate and electrodermal activity was collected. A brief roadmap to this chapter is given in the following paragraphs.

The Simulator Sickness Questionnaire (SSQ) was used to assess cybersickness, with alternatives, pros and cons being outlined in section 3.1. The level of enjoyment was measured by using the short-form Physical Activity Enjoyment Scale (PACES-S) which is outlined in section 3.2. To measure the user's level of exertion, heart rate and in-game travel distance throughout the experiment was measured and is further described insection 3.3. A description of other measured characteristics that might be able to give insight into who might experience cybersickness is made in section 3.4.

A description of the application process to Sikt is described in section 3.5, which is meant to ensure GDPR compliance as well as responsible data collection and processing. This section is mostly meant for a person who is using this thesis as a starting point for their work.

The chapter concludes with describing the experiment design in section 3.6. This section describes every choice that was made about the way that the data was collected. It also describes how the three device versions differ from one another. Structurally, the section starts out by outlining how participants were recruited then moves on to how the device and experiment both were changed between the three rounds, as well as why only three device versions were made.

3.1 Measuring Cybersickness

The use of virtual reality (VR) technology has seen a steep increase since the first VR headset was designed in 1968 [28]. Millions of VR headsets are being sold worldwide, yet a common problem persists. When using VR headsets, users commonly experience symptoms such as discomfort, nausea and dizziness [29]. This collection of symptoms are very similar to those of typical motion sickness to the point where cybersickness may be considered a subtype of motion sickness [30]. The main cause for the differentiation between motion sickness and cybersickness is that cybersickness is mainly induced purely though visuals [30], whereas motion sickness might also be induced by sensory impressions other than visuals, for example by being on a boat. Today, Simulator Sickness [31], Cybersickness [29], VR Sickness [32] and Virtual Reality Induced Sickness Effects (VRISE) [28, p. 5] are all used interchangeably about cybersickness symptoms. In this thesis, the term *cybersickness* is used to refer to this collection of symptoms.

The collection of symptoms that together make up cybersickness, such as nausea, sweating and general discomfort, are difficult to measure. This is in parts due to the general lack of consensus in the field. For example, the terminology used to describe sickness from virtual environments is inconsistent, and there also seems to be no clear answer as to exactly what biological mechanisms might best describe cybersickness [24]. There are many components in a VR system which might influence the users' discomfort, with the main components being hardware technologies and content rendering [33]. With its multifaceted origins rooted in both hardware technologies and content rendering, alongside a lack of consensus in the field, cybersickness shows itself to be a complex issue that presents significant challenges both in research investigation and measurement.

In this thesis, cybersickness is primarily measured using the Simulator Sickness Questionnaire (SSQ), but electrodermal activity was also measured as one paper suggested that it might be correlated with cybersickness [34].

3.1.1 Measuring Cybersickness using Questionnaires

Questionnaires provide a cost-effective and standardized way of assessing the degree to which an individual is experiencing cybersickness. Additionally, questionnaires do not require any additional sensor devices which makes it practical. Given the symptomatic overlap between motion sickness and cybersickness, researchers have adapted questionnaires initially designed for the former to gauge the severity of the latter. Notable among these are the Motion Sickness Suceptibility Questionnaire [35] and the Simulator Sickness Questionnaire (SSQ) [31]. These questionnaires were both originally developed for other purposes, but have both been extensively used within the realm of virtual reality to evaluate the degree of cybersickness experienced by individuals.

The SSQ has gained the strongest foothold in the world of cybersickness assessment. As of spring 2023, the original SSQ paper has been cited more than 5000 times, which is far more than any other proposed cybersickness measurement solution. Derivatives of the SSQ, such as the Cybersickness Questionnaire [36] and more notably the Virtual Reality Sickness Questionnaire (VRSQ) [32], have been developed to better fit VR usage. The items in the VRSQ is a subset of those in the SSQ, so if the users answer the SSQ, the VRSQ score can still be calculated. Nevertheless, the use of questionnaires other than the SSQ have not yet been widely adopted, and the use of the SSQ persists as the standard by which researchers measure cybersickness [28, p. 99].

The Simulator Sickness Questionnaire

The SSQ was developed by Robert Kennedy in 1993 to assess the motion sickness symptoms experienced by military personnel who were undergoing Navy simulators [31]. The questionnaire consists of 16 items, each addressing a distinct symptoms. Participants are asked to rate the degree to which they experience each symptom using a 4-point Likert scale, where a score of 0 denotes the absence of the symptoms, escalating to 3 which indicates a severe manifestation of the symptom [31]. The weight of each questionnaire item and the computation of a total SSQ score is shown in table 3.1. A higher score corresponds to more pronounced symptoms.

In addition to giving a total sickness score, the SSQ also has three subscores which describe different aspects of the user's experience. These symptom clusters are labeled Oculomotor (O;eyestrain, difficulty focusing, blurred vision, headache), Disorientation (D; dizziness, vertigo) and Nausea (N; nausea, stomach awareness, increased salivation, burping) [31]. For VR applications, it is common that the highest subscore is disorientation, followed by oculomotor and lastly nausea [24].

Each item in the questionnaire is weighted according to table 3.1. The Likert scale answer is weighted by either 1 or 0 for each category, and composite scores are calculated by the weighted sum of the questionnaire answers as shown in the bottom of table 3.1. The minimum total SSQ score is 0 and the maximum is 235.62. Any total SSQ above 20 may be considered ”problematic” by some [37], however it is common for VR gaming content to have a total SSQ score around the 30-40 range [24]. For this thesis, scores below 40 will be considered ”acceptable”.

	Weight		
SSQ Symptom[a]	N	O	D
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total[b]	[1]	[2]	[3]
Score			
N=[1] × 9.54			
O = [2] × 7.58			
D = [3] × 13.92			
TS[c] = ([1] + [2] + [3]) × 3.74			

[a]Scored 0, 1, 2, 3.
[b]Sum obtained by adding symptom scores. Omitted scores are zero.
[c]Total Score

Table 3.1: SSQ items and their weightings

Drawbacks of using the SSQ

Despite the widespread use of the SSQ in assessing the severity of cybersickness symptoms, it is not without its flaws. The following paragraphs examines some of the drawbacks of using the SSQ, which will offer a more nuanced understanding of how the SSQ scores may apply to the research questions. Three main drawbacks will be described further: First, the baseline assumption of the SSQ is that there is zero symptom presence, which may not always be accurate. Second, the original design of the SSQ was not specifically crafted with VR applications in mind. Lastly, since the study involves physical exertion when playing the game, certain SSQ items such as sweating, fatigue and general discomfort might be larger than for non-exergame VR games.

The SSQ is based on the assumption that pre-test participants will have a SSQ score of 0. This assumption is not necessarily sound [38]. In the original SSQ paper, the authors explicitly state only to use the questionnaire post-test [31]. Participants that feel unwell at the start of the trial must instead be screened out by asking whether they feel as good as they normally do. By administering the questionnaire both before and after the trial, participants might be primed to score higher in the post-test questionnaire assessment [28, p. 98]. One study found that administering the SSQ both before and after the VR experience lead to biased post-exposure SSQ scores [39]. When administering the SSQ both pre- and post-test, the authors saw an 80% increase in the SSQ when compared to a group that only had the SSQ administered post-test [39].

There is also the fact that the weighting and scoring of the SSQ was not tailored specifically for VR applications. As a result, it may not be fully applicable to the evaluation of cybersickness in virtual reality applications, which have unique features such as 3D immersion and head-mounted displays [28, p.97]. For example, the SSQ does not ask respondents to self-assess their postural instability (or feeling of imbalance), which other more VR-specific questionnaires ask about [40]. This lack of tailoring can lead to inaccurate assessments and hinder the development of effective interventions for cybersickness. However, due to the fact that so much research has been done on cybersickness which uses the SSQ as a metric, the SSQ was chosen as the way to measure cybersickness in this thesis, as this allows for the efficient comparison with other VR applications.

During the trials, participants were encouraged to navigate around the track as rapidly as possible, aligning with the intended usage of the exergame platform as a workout apparatus. This instruction could potentially inflate the presence of certain symptoms captured by the SSQ, such as "general discomfort", "fatigue" and "sweating".

3.1.2 Measuring Cybersickness using Physiological Measurements

Objective ways of measuring cybersickness include Electrodermal Activity (EDA), Electrocardiography, gaze, Electroencephalography, Electromyography, blood pressure, electrogastrography and postural sway [28, p. 99]. Most relevant to this thesis is ED, as measuring these quantities is simply done by using wearable sensors such as a and a smart watch. As such, EDA was measured in the tests using an Empatica 4 smart watch, as this measure is not so invasive as to cause further discomfort to participants.

Measuring EDA in the participants' wrist might to some extent help in assessing the participant's cybersickness levels. Some research suggests that EDA might be used as an indicator of cybersickness [28, p. 100]. In one study, the researchers managed to reduce the level of cybersickness in participants by having the in-game control signal decrease in real-time as the rate of change of EDA increased [34]. This suggests that EDA and the level of cybersickness is linked, and as such measuring EDA levels might provide information about the participants' real-time cybersickness experience.

Note that EDA has been widely used as an indicator for emotional arousal, stress responsivity or physical effort [41]. Because EDA is sensitive to such a wide variety of stimuli, any interpretation needs to be carefully considered. This is particularly true for the purpose of using cybersickness using EDA on an exergame platform. In this thesis, EDA might not appear to be related to cybersickness, as users might have an increased EDA from physical effort and not from cybersickness.

3.2 Measuring Enjoyment

Another metric that is useful in evaluating the research questions is whether or not participants enjoy playing the VR game. If it is found that participants enjoy playing the VR game just as much as they enjoy other kinds of physical exercise, then getting and setting up this rig might not be worth the trouble for a majority of wheelchair users. The ideal situation would be that they enjoy it far more than regular physical exercise, all the while playing a VR exergame is easily accessible to them and something wheelchair users can do in their home.

As outlined in section 3.1, the participants already filled out a questionnaire to assess cybersickness severity. Adding a more questions to this questionnaire is a low-cost way of also assessing participants' enjoyment of the activity. In order to prevent respondent fatigue, the questionnaire to assess the participants' enjoyment should be short. This section first describes the Physical Activity Enjoyment Scale (PACES) before moving on to describe the shorter version of the PACES which was used in the study.

The Physical Activity Enjoyment Scale

A common way to assess the enjoyment of physical exercise is the Physical Activity Enjoyment Scale (PACES). PACES is a self-report questionnaire designed to measure an individual's level of enjoyment towards physical activity. The scale consists of 18 items, each rated on a 7-point Likert scale, where 1 indicates ”strongly disagree” and 7 indicates ”strongly agree”. The questions are designed to assess various aspects of physical activity enjoyment, including the perceived level of challenge, the degree of enjoyment, and the overall experience of the activity. A higher PACES score means the physical activity is more enjoyable. Some examples of questions from the PACES include ”I enjoy doing this activity”, ”I find the activity very pleasant”, and ”This activity is not very enjoyable” (reverse scored) [42]. The scores from the PACES can be used to determine an individual's level of enjoyment towards a specific physical activity, which may be useful in designing exercise programs that are more enjoyable and thus more likely to be sustained over time.

The Short Physical Activity Enjoyment Scale

The Short Physical Activity Enjoyment Scale (PACES-S) is a brief version of the original PACES developed in 2021 [43]. It consists of 4 items from the original questionnaire and is designed to be a faster and almost as reliable alternative to the original 18 item questionnaire. The format of the questions are similar to those of the original PACES, but with significantly fewer items. In PACES-S, users are asked to rank the items presented in table 3.2 on a 5-point Likert scale, where 1 indicates ”strongly disagree” and 5 indicates ”strongly agree”. The items in the questionnaire are shown in table 3.2. The lowest score will thus be 4, and the highest score is 20. The higher the score, the better.

Number	Item
1	I enjoy the activity
2	I find the activity pleasurable
3	I find the activity very pleasant
4	The activity feels good

Table 3.2: The items in the PACES-S questionnaire

The PACES-S has been found to have good reliability and validity in measuring enjoyment of physical activity [44], and it is a useful tool for researchers and practitioners who need a brief measure of physical activity enjoyment. Using the full version PACES would have made the overall questionnaire too long, which could result in reduced participant engagement and response quality [45]. Because of this, the PACES-S was chosen to minimize the risk of respondent fatigue in participants.

3.3 Measuring Exertion

The exergame platform is assessed as an exercise device, and so user exertion is interesting to analyse when assessing the device performance. One way to measure exertion is to use subjective measures such as questionnaires or self-reports. Exertion could have been measured by asking users to rate their perceived level of exertion in the questionnaire, but this was somehow overlooked when designing the questionnaire. As such, heart rate and distance travelled in-game was used as a measure of exertion in users.

Heart rate is a valuable tool for assessing a person’s level of exertion during exercise because it provides an objective measure of how hard the body is working. When a person exercises, their heart rate increases as the heart pumps more blood to the muscles to provide the necessary oxygen and nutrients for energy production [46, p. 256]. The higher the intensity of the exercise, the higher the heart rate will be [46, p.148]. By monitoring heart rate during the experiment, an insight into the individuals’ level of exertion is gained. It is a non-invasive and inexpensive method of assessing exertion level, making it fit for use in the study conducted in this thesis.

When using the exergame platform, it is likely that the in-game velocity of the player is related to their level of exertion. Generally, higher velocities are likely to mean a higher level of exertion, although this metric will vary with how trained an individual is. Recording this data is simple to do and might provide additional insights during data analysis.

3.4 Other Measurements

Additional information was also collected through additional questions in the questionnaire. These included cardio exercise habits, how prone to motion sickness the user is, VR habits as well as the user's age, gender and height.

Recording the participants' cardio exercise habits is useful as it provides insights into their fitness and overall health status. Understanding the cardio exercise habits of the users might help identify potential confounding factors that can influence the study's results. For example, individuals who engage in regular cardio exercise might have a higher fitness level than those who don't, which may impact their performance in the exergame platform. Research has suggested that young adults who are more physically active have a better sense of balance [47], which might make individuals more prone to experiencing cybersickness [40].

Insights into the user's susceptibility to general motion sickness can be helpful when searching for differences between people who do and do not experience cybersickness when using the exergame platform. Users who are prone to motion sickness may be more likely to experience cybersickness when using the exergame platform [28, p. 94]. In contrast, users who are less susceptible to motion sickness may exhibit greater tolerance to VR stimuli, resulting in reduced negative symptoms associated with cybersickness. Therefore, collecting information about users' susceptibility to motion sickness can provide valuable insight into how they may respond to the VR experience. In this thesis, whether or not users are susceptible to motion sickness was done through a self-assessed yes/no question.

Collecting information about VR habits can be valuable when evaluating the performance of the exergame platform as it can offer insight into the users' familiarity with VR technology. Users who have prior experience with VR technology may for example exhibit greater comfort and reduced susceptibility to cybersickness [48], whereas those who are inexperienced may be more vulnerable to negative symptoms associated with VR.

The users' age was recorded as an indicator of cybersickness susceptibility. The research on cybersickness and age is somewhat contradictory, where some research suggests that older individuals may be more susceptible to cybersickness when compared to younger individuals [28, p. 53]. Other research has shown that cybersickness susceptibility peaks at 12 years old and decreases sharply from there on [49]. One possible explanation for this is that younger individuals may be more tolerant to the VR stimuli because they have more experience with gaming and the use of displays than older people [28, p.53].

Research has indicated that females are at higher risk of cybersickness [50]. Sex has been stated as being a characteristic likely to predict motion sickness [51]. Because of this, it might be insightful to compare the SSQ scores between males and females. Users were asked for their gender so that it might be possible to detect the differences between how men and women perform.

Finally, the user's height was requested through self-reporting in the experiment questionnaire. This was primarily assessed due to the physical setup of the exergame platform. It has been found that the wheelchair does not sit completely still on the platform when the user pushes the wheels. In fact, it bobs somewhat back and forth. The user's height might influence how much the wheelchair moves upon pushing the wheels, as tall people might have a higher center of mass that is also further towards the front of the wheelchair.

3.5 Application to Sikt

The research questions posed in this thesis cannot be answered without study participants. When collecting data from people, there is the need to ensure that this process conforms to the European privacy laws, namely the General Data Protection Regulation (GDPR).

An application was sent to Sikt (the Norwegian Agency for Shared Services in Education and Research), which gave guidance on how to ensure GDPR compliance when collecting and analysing data. The application has been included in appendix D. Participants needed to fill out a consent form which indicates clearly what the data will be used for, how it will be used, that participation is voluntary and that participants may withdraw from the data collection at any point in time without providing a reason for doing so. The consent form has been included in appendix E.

It is worth mentioning that at the time of the Sikt application submission, the thought was to also include wheelchair users in the tests. This explains why the application describes that two different groups of study participants will be used. Due to the early results from testing on able-bodied individuals being relatively poor, testing on wheelchair users was dropped. This is further explained in section 3.6.3.

3.6 Experiment Design

The overarching goal of this thesis is to assess how well the exergame platform performs in an imagined typical use-case, so the type of game that was tested was a racing-type game. Users race around a track to try to achieve the best lap time possible. Free, continuous movement is shown to be the most cybersickness-inducing movement type [24] and therefore such a use-case will test the device when used at its limit.

Since the study takes place in Norway, the questionnaire and consent form was made available both in Norwegian and English. The translation of the items of the SSQ is given in appendix B and the translation used for the PACES-S is given in appendix C. The exact translation of each item in the questionnaire is also given in appendix F.

In-depth guidelines for completing one trial are given in appendix G. Prior to showing up, users were encouraged to dress in clothes fit for exercise. Participants started out by filling out the consent form in appendix E before attaching a heart rate belt (Polar H10) and the Empatica 4 to measure EDA. The participant was told that they may end their play time early if they feel extremely ill, but they are encouraged to play for as long as possible. Then, the user puts on the VR headset and plays for 10 or 15 minutes, until the game automatically stops them from playing. The participant then immediately fills out the questionnaire in appendix F. After the questionnaire is filled out, the test is complete. Participants gave written consent on whether or not they are able to participate multiple times. In the case of being able to participate in multiple tests, participants might be contacted one additional time to participate in another test of a different device version.

3.6.1 Recruiting Participants

Two methods of recruitment for the experiment were used. One method involved outreach through personal and professional networks and was used for all three test rounds. The second strategy involved hanging up posters in public spaces and was done upon the need for a larger sample size when testing the final version of the device. Additionally, for the final test round, gift cards valued at 50NOK was given to each participant, which made it easier to recruit more people by word-of-mouth.

The recruitment of participants through personal networks involved contacting individuals who had previously shown an interest in the device or friends who might be interested in testing it. Participants were given details about the experiment like the purpose and time commitment. In this introduction they were also shown a short video demo of the exergame platform. Participants were encouraged to spread the word to anyone they thought might find the project interesting. The drawback of this approach is that the group of participants is bound to be quite homogeneous in interests, age, education level and, as it turns out, ethnicity. This strategy, however, proved to be very effective, and most of the participants were recruited this way.

As for recruiting through posters, this was mainly done by hanging up posters close to VR labs at NTNU. This is because it would be interesting to see how individuals with more VR experience performed in the game. The poster that was developed for this purpose is included in appendix H. Sadly, this strategy proved to be ineffective, as only four people signed up after seeing the poster. The bright side is that the four people that signed up were avid users of VR, with all of them self-reporting a high VR gaming frequency.

Changing plans for the sampled population

As is evident from the application made to Sikt (appendix D), the initial plan was to test the device with two different populations: able-bodied paricipants and wheelchair users. After the second round of testing frankly yielded abysmal results, the choice was made to drop testing on wheelchair users and rather focus on the development of the device itself by testing on easily accessible participants, namely other students.

Another reason why wheelchair users were dropped, is because there is no reason to expect that wheelchair users would experience *less* cybersickness than able-bodied users when testing the device. In fact, it is reasonable expect that since wheelchair users' normal mode of transportation is by wheelchair, they are more likely to notice the inconsistencies between input and output(of what they're seeing in VR) more acutely. This acute awareness of the movement mismatch might lead to wheelchair users being more prone to cybersickness when using the exergame platform [28, p. 5].

The great weakness of this thesis is that wheelchair users were not directly consulted during the development of the device. The project was, however, done in collaboration with the Department of Neuromedicine and Movement Science (INB) at NTNU, particularly with researchers that work with the target population. The development of the device has been discussed and guided by these researchers. If the initial cybersickness responses had been less concerning, efforts would have been made to get in touch with and measure the response of wheelchair users.

3.6.2 Iterating with Limited Information

As will become clear in chapter 4, the quantitative metrics that were used to assess the performance in the device were very spread out. For the early iterations of the device with a very limited sample size, it was therefore difficult to draw any meaningful information from the quantities the questionnaire and sensors yielded. The level of cybersickness varied a lot from person to person, and participants seemed to find different things sickening. There is also the possibility that the user's level of cybersickness might vary with several factors that are hard to control for, for example how much coffee they have drunk, how well they slept or how hungry they might feel.

The most valuable feedback for the early iterations proved to be the qualitative feedback given by each individual user. Oral feedback was noted down in real-time as the user was taking the test. The user also had the opportunity to provide free-form feedback in the questionnaire. Using this feedback, changes were made to the game controller and the way the experiment was set up. This qualitative feedback formed most of the basis for the iterations described in sections 3.6.3 and 3.6.4.

3.6.3 Iterations on the Experiment

Test Round	Play time
1	15
2	10
3	10

Table 3.3: Parameters for experiment rounds

As shown in table 3.3, the test time was reduced from round 1 to 2, from 15 to 10 minutes. Cybersickness symptoms seem to be most pronounced in the 10-20 minute play time range with SSQ scores being lower for both less than 10 and more than 20 minutes of play time [24]. Because of this, the initial test time was chosen to be 15 minutes. The test time was decreased to 10 minutes due to two reasons: 1) half of the participants in the first round ended the trial early due to nausea and 2) the participants that did complete, said that the play time felt too long. Because of this, the play time was reduced to 10 minutes, which is still within the 10-20 minute range but feels substantially shorter to participants.

3.6.4 Iterations on the Game Controller

Most of this thesis is about the development and evaluation of the exergame platform. The game controller (or device) itself is the area where most of the changes were made. For the most part, the way that the signal is clamped and scaled, introduced in section 2.5 have been the variables that have been changed between each experiment. Essentially, these variables define the ceiling for the turn speeds that a user should be able to input to the game, and a scaling factor by which the signal is multiplied prior to clamping. The goal is to create a usable device, and so changing other aspects, such as improving the turning mappings outlined in section 2.4.3, was also done. The same notation that was used in section 2.5 applies in this section, with $\omega'\text{max}_p$ denoting the clamping value for the angular velocity input and $v\text{max}_p$ denoting the clamping value for the linear velocity input of the player.

As explained in section 3.6.2, it proved difficult to draw any intuition as for how to iterate upon the game controller solely by looking at numerical data. Instead, the most valuable feedback was obtained from the open-ended free-form text responses at the end of the questionnaire as well as real-time verbal feedback. Based on this feedback, efforts were made to address the issues identified by the participants in each iteration of the device.

Prior to the official testing of each device version, extensive testing was done by the author. Although this is purely subjective, each version was tweaked until the problems with the previous version of the device were less apparent. For example, if multiple users claimed that the turning signal felt too sensitive, the sensitivity was reduced.

A summary for each device version is shown in table 3.4 and is elaborated upon in the following paragraphs.

Device Version	$\omega'\mathrm{max}_\mathbf{p}$	**Turn Signal Limiting Scheme**	**Turn Signal Mapping**
1	150	Clamp	Linear
2	30	Clamp	Linear
3	150	Scale and clamp	Slow start

Table 3.4: Parameters for device versions

Device Version 1

The first version of the device left the signals ω_p and v_p from the equations in section 2.3 largely unchanged. The linear mapping eq. (2.24) was used, and the The turning signal was clamped at ± 150 [deg/s] while the linear velocity was clamped at ± 3.5 [m/s].

In terms of the signal processing and limiting terms introduced in sections 2.4 and 2.5, the signal processing for game controller version 1 is shown below.

$$\begin{aligned} \text{Turn signal processing :} \quad & \omega'_p = m \cdot \text{linear}(\omega_p) \\ v\text{max}_p : \quad & \pm 3.5\text{[m/s]} \\ \omega'\text{max}_p : \quad & \pm 150\text{[deg/s]} \end{aligned}$$

Device Version 2

Testing version 1 of the device made it clear that `max_turn_rate`=$\pm 150 deg/s$ was far too high. Every single participant mentioned that it was too sensitive and that they felt like they had little control. Because of this, the only change from version 1 is that the turning signal was clamped at $\pm 30 deg/s$.

In terms of the signal processing and limiting terms introduced in sections 2.4 and 2.5, the signal processing for game controller version 2 is shown next.

$$\begin{aligned}\text{Turn signal processing}: &\quad \omega'_p = m \cdot \text{linear}(\omega_p)\\ v\text{max}_p: &\quad \pm 3.5[\text{m/s}]\\ \omega'\text{max}_p: &\quad \pm 30[\text{deg/s}]\end{aligned}$$

Device Version 3

Feedback from participants on version 2 of the device showed that simply reducing the clamping value did not alleviate the problem where the in-game character would turn when the user did not intend to turn. If users did not apply *exactly* the same amount of force, version 2 would be very prone to turning. Additionally, users claimed that the device felt both too sensitive and not sensitive enough at the same time. That is, it was very easy for the in-game character to start turning, but the maximum turning value was not very high. This feedback formed the basis for the changes done between device version 2 and 3.

The slow start turning mapping was implemented as described in section 2.4.3. Before running a new test round, however, it became apparent that when the turning signal was left unscaled, the signal would often simply clamp out at the threshold values, leaving the user with little feeling of control. As a result, the author tested the game controller with various scaling values and found that a scaling factor of 0.25 provided a sufficiently good level of control.

In terms of the signal processing and limiting terms introduced in sections 2.4 and 2.5, the signal processing for game controller version 3 is shown below.

$$\begin{aligned}\text{Turn signal processing}: &\quad \omega'_p = m \cdot \text{slow start}(0.25 \cdot \omega_p)\\ v\text{max}_p: &\quad \pm 3.5[\text{m/s}]\\ \omega'\text{max}_p: &\quad \pm 150[\text{deg/s}]\end{aligned}$$

3.6.5 Why Only Three Device Versions?

The device only underwent three iterations. The initial plan was to run multiple iterations of the device with between 5-10 participants testing each iteration. After having completed testing rounds 1 and 2, it became evident that the collected data was so spread out that it would be hard to draw any definite conclusion with such small sample sizes. As such, it was decided that the third and final version of the device would be tested with a larger sample size so as to make any conclusions about the research questions more certain.

An additional benefit to this is that by using a larger sample size for the final device version, a better basis was formed so that a more effective comparison of results from this device might be done with later iterations of the exergame platform. Further improving the device or gameplay experience is indeed one of the suggestions for further work. By having a larger sample size for the final version of the device, the trends in the data are less likely to be mere chance.

4

Data Analysis

This chapter presents the processing, analysis and interpretation of the data collected during the experiments. The aim of this chapter is to gain insight into the relation between different factors affecting users' cybersickness symptoms, sense of enjoyment, and user experience in the context of the exergame platform.

A lot of different data has been collected, and there are many ways to compare and analyse the data. After having performed extensive data analysis on all the collected data, a few particularly interesting relationships were identified. In answering each research question, the most relevant relationships and data are highlighted. This way, the risk of giving readers an information overload is reduced while still highlighting the key findings from the data.

Insights and conclusions about the research questions will be drawn from the collected and analysed data. The findings from this chapter will also be linked to existing literature where applicable. Structuring it this way this makes for a better reading flow. This structure is meant to enhance the reader's understanding of the findings and how they relate to the research questions. Additionally, the structure makes sets the research in context with findings within the broader academic landscape.

The chapter starts off by describing how the data for each participant was processed, then moves on to describe the methods used to answer each research question. The research questions are then answered section by section. Variables that show a clear relationship will be presented earlier, while variables that have a less clear relationship will be presented later in each section. Section 4.1 investigates the relationship between the device configuration, cybersickness and enjoyment. Section 4.2 investigates the factors that contribute to a good user experience, while section 4.3 aims to find some characteristics of cybersick individuals.

Data Preprocessing

To process raw data into meaningful information, python alongside the pandas, scipy and numpy libraries were used. All the scripts that have been developed in the writing of this thesis have been thoroughly documented and are included in the ”Data Analysis” folder of the zip delivered with the thesis.

The collected data from the sensors needs to be combined with the survey data in a meaningful way. ”Sensor data” will in this case be all data that has real-time data points, which encompasses the Empatica output, heart rate belt output and game logging output. By using the UNIX timestamps for the heart rate belt, Empatica and game, all sensor data was trimmed. The trimming process involved removing data points from the Empatica and heart rate belt that were collected when the game was not running. This also the need to synchronize the start of sensor data sampling when performing the experiments.

After trimming, the sensor data is further processed. From the Polar heart rate belt, the average heart rate is derived from the datapoints using eq. (4.1). The average values for the Empatica sensor, namely EDA, is calculated in the same way using eq. (4.1). In the Python code implementation, this was done by loading the output from the sensors as a pandas dataframe [52], then calling the mean function after having trimmed the data as described in the previous paragraph.

$$\bar{y} = \frac{1}{N} \sum_{n=1}^{N} y[n] \tag{4.1}$$

To compare heart rates across age, the mean percent of the estimated maximum heart rate was used in the analysis. The maximum heart rate was estimated using eq. (4.2), where the formula is developed by Hill et al for upper body cardio exercise [53]. Each participant’s average heart rate was then calculated as a percentage of the maximum estimated heart rate, $\%\text{HR}_{\text{peak}}$, by using eq. (4.3). After having talked to wheelchair exercise researchers from the Department of Neuromedicine and Movement Science at NTNU, the intensity levels table 4.1 were used to assess the level of intensity the user experiences. The intensity zones have been calculated based on data collected in Carlsen et al [54] in a similar upper-body exercise modality as wheelchair propulsion.

$$\text{HR}_{\text{peak}} = 220 - \text{age} - 20 \tag{4.2}$$

$$\%\text{HR}_{\text{peak}} = \frac{\text{HR}_{\text{avg}}}{\text{HR}_{\text{peak}}} \tag{4.3}$$

Intensity	**$\%\text{HR}_{\text{peak}}$**
High	87-97%
Mod	75-86%
Low	55-75%

Table 4.1: Heart rate zones for upper body exercise

The game logs the cumulative movement and rotation of the player. Since the game automatically ends after 10 minutes, the average movement and rotational speeds of the player was found by dividing the final datapoint for cumulative movement and rotation by 600 seconds.

Analysis Methods

To gain insight into trends in the data, four separate ways to analyse the data were done. Correlations were calcuated and inspected, scatter plots were drawn, statistical tables were calculated and finally word clouds were illustrated. All the code that has enabled the data analysis has been included in the ”Data Analysis” folder of the thesis zip deliverable.

Correlations and p-values of relevant continuous variables was calculated and analysed. This was done using the Pearson correlation coefficient. Pearson’s correlation coefficient assumes there is a linear relationship between variables, that the random variables are continuous, that the variables are normally distributed and that they are independent of each other. Correlations of -1 or 1 imply an exact linear relationship, and 0 implies no correlation [55]. Positive correlations imply that as x increases, so does y. Negative correlations imply that as x increases, y decreases.

Additionally, the two-sided p-value was calculated for each correlation coefficient. The null hypothesis is that the underlying distributions of the samples are uncorrelated and normally distributed. The p-value then describes ”the probability that abs(r’) of a random sample x’ and y’ drawn from the population with zero correlation would be greater than or equal to abs(r)” [56].

The correlations were calculated using scipy in Python, specifically the *pearsonr* function [56]. This function gives the correlation coefficients and corresponding p-values as described above.

For categorical variables such as gender and self-reported proneness to motion sickness, the point-biserial correlation coefficient was calculated. This is very similar to calculating Pearson’s correlation coefficient, and in practice this boiled down to converting dichotomous categories into 0 and 1 rather than strings. This was done for the variables shown in table 4.2. The interpretation of the coefficients remain the same.

The correlation coefficients of the most interesting variables, as well as their associated p-values, have been included in appendix I.

Variable	**1**	**0**
Motion Sick prone?	Yes	No
Gender	Female	Male

Table 4.2: Numerical values of dichotomous variables

Scatterplots are also used extensively in this chapter. The datapoints are given in black unless otherwise stated, and the means and standard deviations may be given in red.

Box and whisker plots make an appearance in this chapter. The ends of the whisker denote the minimum and maximum values, and the diamond shapes denote outliers. The box itself denotes the thresholds for the upper and lower quartiles of the data, which is where 50% of the data is found. The line that splits the box in two is the median.

Statistical tables are used for more specific metrics of certain distributions. These tables will include metrics such as the median and mean values of a metric, but also the minimum and maximum values of the metric in the data set. These values have been calculated by using the *describe* function on a pandas dataframe [52].

Word clouds are used for analyzing free-form feedback given by participants. More frequently used words are larger in a word cloud. They are useful for getting a quick overview of the most prominent topics of in a text. In this thesis, the Python library WordCloud [57] was used to generate wordclouds.

4.1 Device Impact on Cybersickness and Enjoyment

This section addresses the first research question, where the metrics of the experiment across device versions is analyzed.

In this section, the focus will be on answering RQ1, given below. Understanding the impact of wheel speed processing on users' experiences is crucial to optimizing the exergame platform's design and ensuring a more engaging and enjoyable virtual reality experience for wheelchair users.

> **RQ1:** How do users' cybersickness symptoms and sense of enjoyment vary with the way the wheelchair wheels' rotational speeds are processed in the exergame platform?

To assess the severity of the cybersickness symptoms that users may experience, it is necessary to look at the participants' scores from the SSQ. A secondary metric that gives some additional insight into the level of discomfort that users experience is the dropout rates. While participants were encouraged to play for the entire duration, they were also informed that if the discomfort felt unbearable, they were allowed to end early.

In total there were 3 device versions, where the first two versions was often described by participants as being ”difficult to control”. The number of participants for each test round is shown in table 4.3. The test participants were the same individuals for rounds 1 and 2, except for one who expressed that they did not want to participate for round two. Round 3 featured an entirely new set of participants. As seen by the mean and standard deviation of the ages, the people who participated are mostly fairly young adults.

Test round	Total Participants	Male	Female	Mean age (SD)
1	6	3	3	26.11 (2.23)
2	5	2	3	26.27 (2.47)
3	26	14	12	25.95 (3.11)

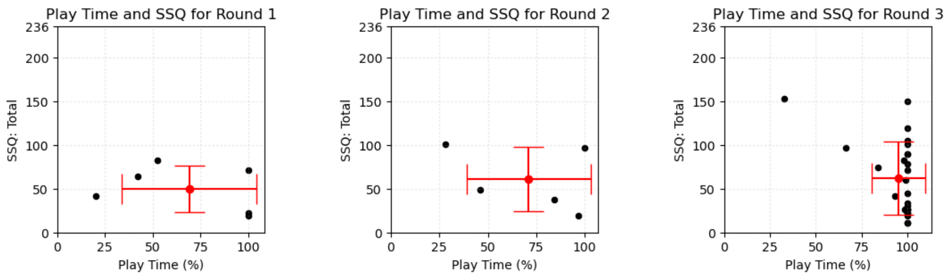
Table 4.3: Participants, gender and age distribution of test rounds

4.1.1 Play Time

Figure 4.1 shows that the average user's percentwise completion of the full play time in the study increases only slightly from round 1 to round 2, but significantly from round 2 to round 3. The exact metrics for the play times are summarized in table 4.4. The mean and median cybersickness scores seem to increase steadily, but the standard deviations in the SSQ scores are so large that this might simply be due to randomness. Table 4.5 gives the exact numbers displayed in the plot.

A possible explanation for participants engaging in the exergame platform for longer periods could be that they find the gameplay less jarring with each subsequent iteration. This might be what primarily lead them to play for longer in the final round. However, improvement to the gameplay experience might inadvertently lead them to both move more around in VR and play for longer, which again might worsen cybersickness symptoms due to participants being more exposed to the sensory conflict inherent in the VR experience.

In light of these observations, future iterations of the platform should focus on identifying and addressing the factors that contribute to cybersickness while maintaining or enhancing user engagement. The ultimate goal is to enable users to play for extended periods, ideally up to 30 minutes, without experiencing significant discomfort. By understanding the interplay between gameplay smoothness and cybersickness, developers can optimize the exergame platform to provide a more enjoyable and sustainable virtual reality experience for wheelchair users.



(a) Playtime and SSQ for round 1 **(b)** Playtime and SSQ for round 2 **(c)** Playtime and SSQ for round 3

Figure 4.1: Play time and SSQ for the test rounds, with means and standard deviation in red.

Total Play Time statistics over the rounds						
Round	Count	Median	Mean	SD	Min	Max
1	6	76.22	69.19	35.32	20.33	100.00
2	5	84.50	71.17	32.12	28.33	100.00
3	26	100.00	95.10	14.57	33.00	100.00

Table 4.4: Play time statistics over rounds

4.1.2 Cybersickness Levels

Figure 4.2 shows a box and whisker plot for the SSQ subscores for each test round. The medians are the bold red lines. The plot shows that for round 1 and 3, the SSQ subscores generally matches the profile of typical cybersickness, with disorientation being the highest, followed by nausea and then oculomotor. The participants in test round 2 seemed to experience most nausea. Literature has referred to the SSQ subscore profile seen in round 2 as ”space sickness” [58].

Due to the small sample sizes (n=6, n=5, and n=26), it is difficult to derive definitive conclusions from the data. However, attempted improvements on the device are unlikely to have drastically changed the degree to which participants experienced cybersickness. For all iterations of the device, the mean and median levels of cybersickness are all considered above what was defined as acceptable in section 3.1.1, that is a total SSQ score of 40. It might therefore be worth investigating whether changes to the game will alleviate cybersickness symptoms. For example, game styles that do not involve continuous movement might be more effective at reducing cybersickness symptoms than further improvements to the device itself.

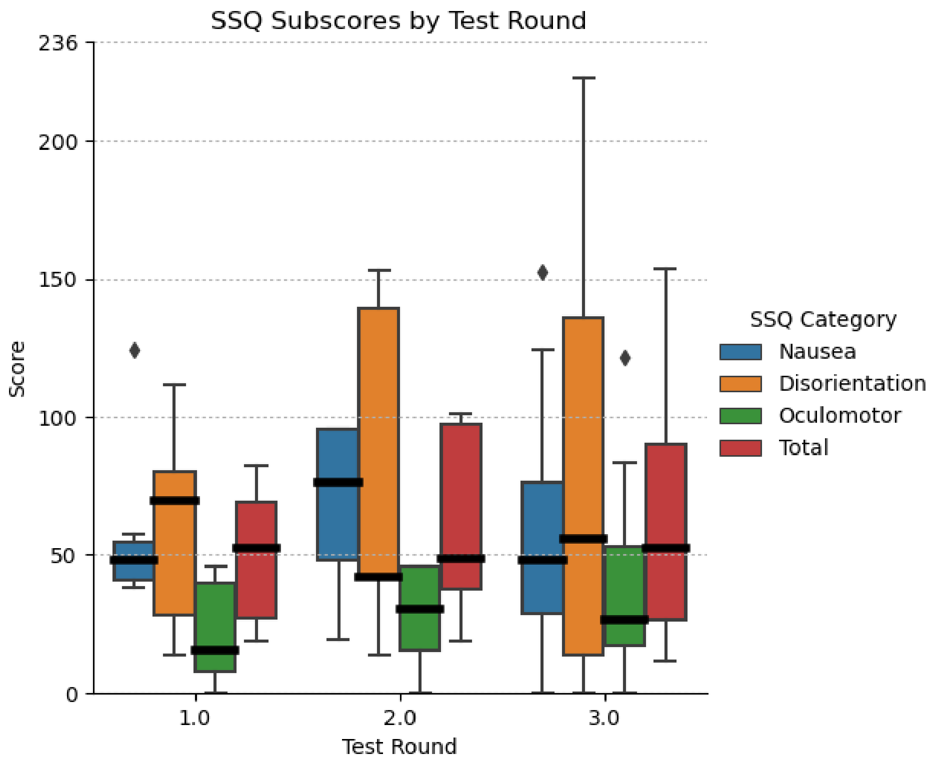


Figure 4.2: Box plots of SSQ subscores by test rounds. The black horizontal lines are medians.

Total SSQ Score statistics over the rounds						
Round	Count	Median	Mean	SD	Min	Max
1	6	52.36	49.87	26.41	18.70	82.28
2	5	48.62	60.59	36.78	18.70	100.98
3	26	52.36	62.00	42.08	11.22	153.34

Table 4.5: Total SSQ Score statistics over rounds

Moving on, fig. 4.3 suggests that individuals who are less prone to motion sickness generally experience lower levels of cybersickness while using the exergame platform. As shown in table 4.6, the mean SSQ score of individuals who are not prone to motion sickness is relatively steady, whereas more motion sick prone individuals' SSQ score increases from round to round. This observation highlights the importance of obtaining a representative sample of users who are and are not prone to motion sickness to accurately evaluate the platform's effectiveness. Individual differences, particularly motion sickness susceptibility, might greatly impact results and conclusions drawn from observations.

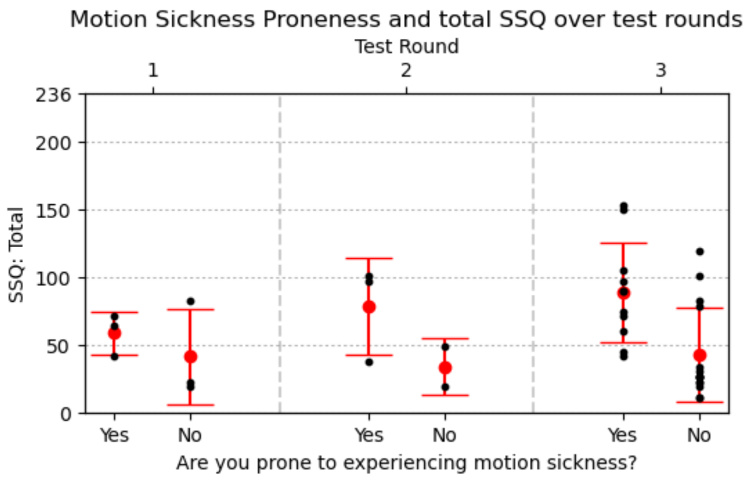


Figure 4.3: Participants' proneness to motion sickness and SSQ by test rounds, means and standard deviation in red.

Round	MS Prone?	Total SSQ Score			
		Count	Median	Mean	SD
1	Yes	3	63.58	58.59	15.57
	No	3	22.44	41.14	35.67
2	Yes	3	97.24	78.54	35.67
	No	2	33.66	33.66	21.15
3	Yes	11	89.76	88.74	37.07
	No	15	26.18	42.38	34.73

Table 4.6: Motion sickness proneness and SSQ score statistics across rounds

4.1.3 Enjoyment

To assess how users' enjoyment varied across device iterations, an analysis of the PACES-S scores have been done. This evaluation aimed to investigate how enjoyment varied as the exergame platform underwent improvements. Based on the PACES-S means in fig. 4.4, it is not clear whether the improvements to the device affected how much participants enjoyed using it. In table 4.7 shows that the fluctuation in both means and medians from round to round are so minor, and the standard deviations so large that any effect the different versions of the device has had on the enjoyment is deemed to be negligible. Similarly to cybersickness levels, there is a consistent discrepancy between individuals who are and are not prone to experience motion sickness. These findings suggests that factors other than the game controller itself may be more influential to user enjoyment.

Oral feedback from the participants supports this hypothesis. During the third round of play testing, when the player controls were deemed satisfactory, many participants shifted their focus towards issues with the game's visuals. This feedback indicates that the decrease in enjoyment may be attributed to the game or VR experience itself, rather than the controller. These findings are further discussed in section 4.2.3.

As will be described in section 4.2, there seems to be a clear relationship between cybersickness and enjoyment.

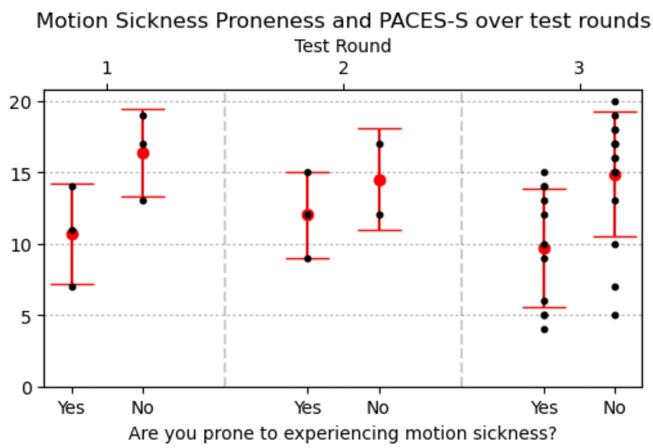


Figure 4.4: Participants' proneness to motion sickness and PACES-S by test rounds, means and standard deviation in red.

Round	MS Prone?	PACES-S Score			
		Count	Median	Mean	SD
1	Yes	3	11.00	10.67	3.51
	No	3	17.00	16.33	3.06
2	Yes	3	12.00	12.00	3.00
	No	2	14.50	14.50	3.54
3	Yes	11	10.00	9.73	4.15
	No	15	15.00	14.87	4.36

Table 4.7: Motion sickness proneness and PACES-S score statistics across rounds

4.2 The Good User Experience

An analysis of how users' experience of the test rounds across the three iterations follows. Recall the second research question of this thesis:

> **RQ2:** What factors contribute to a good user experience in a VR wheelchair simulator, and how do they relate to the design and implementation of the exergame platform?

What are important factors to consider when assessing the user experience of the exergame platform? First and foremost, since the platform is intended to be used for training purposes, it needs to enable users to elevate their heart rate. As was also discovered when analyzing the free-form feedback, it is also important that users feel that the controls are realistic and intuitive. The platform will ideally act as a fun and accessible alternative to more conventional exercise forms. In order to be fun and accessible, the symptoms associated with cybersickness should not be too high, as this might scare users off from using it more than once.

Recall that the PACES-S is a self-assessed questionnaire that aims to assess how much an individual enjoys the physical activity in question. It is therefore reasonable to assume that an individual that had a good user experience is likely to score highly on the PACES-S. Because of this, it is useful to analyze how other variables relate to the PACES-S. Is there a relationship between the PACES-S score and other variables?

By looking at the p-values of fig. 4.5, the PACES-S score seems to be significantly associated with gender, motion sickness proneness, SSQ score, play time, heart rate, movement and turning speeds. Of these variables, the ones that are most strongly correlated with the PACES-S score are SSQ, movement speed, motion sickness proneness, play time and the participants' average heart rate as a percentage of their estimated max.

Since the research question aims to find out factors contributing to a good user experience, some of the significantly correlated variables will not be assessed further. The variables that have been left out are motion sickness proneness, movement speed and play time have been left out from the analysis. Participants' motion sickness proneness is something that the device will not be able to affect. Additionally, movement speed and play time are likely to be very directly related to how cybersick an individual becomes, and so an analysis of this data has also been left out of this section.

The data that will be considered when evaluating the user experience of the device, is mainly PACES-S in relation to heart rate and SSQ. Data from the final testing round with $n = 26$ is used in this section, apart from the analysis of the free-form feedback in section 4.2.3 where data from all testing rounds is used. In this section, the findings related to the research question will be presented in a descending order, where the strongest correlations are presented first, while the weakest correlations and other findings whose relation is uncertain are presented at the end of the section.

Correlation coefficients and p-values for PACES-S

	r	p
Gender	-0.420575	0.032403
MS prone	-0.526134	0.005765
VR habits	0.050031	0.808226
Cardio habits	0.016348	0.936822
Height	0.263732	0.192975
Age	-0.014912	0.942361
SSQ: Total	-0.816608	0.000000
Play Time (%)	0.459274	0.018262
$\%HR_{peak}$	0.442105	0.023735
Avg EDA	0.044786	0.828020
Avg Movt Speed	0.749678	0.000010
Avg Turn Speed	0.690125	0.000096

Figure 4.5: Pearson's correlation coefficient and two-sided t-test p-values for PACES-S

4.2.1 Cybersickness Levels

As expected from the correlation coefficient, there seems to be a very clear relationship between the SSQ and PACES-S scores. This is also shown in fig. 4.6, where the PACES-S score decreases as SSQ gets higher. Although correlations say nothing about causality, it is reasonable to assume that users who experience a lot of cybersickness will enjoy the gaming experience less. Since the relationship between the PACES-S and cybersickness scores seems to be clear, one factor that likely contributes to a good user experience is the absence of cybersickness symptoms.

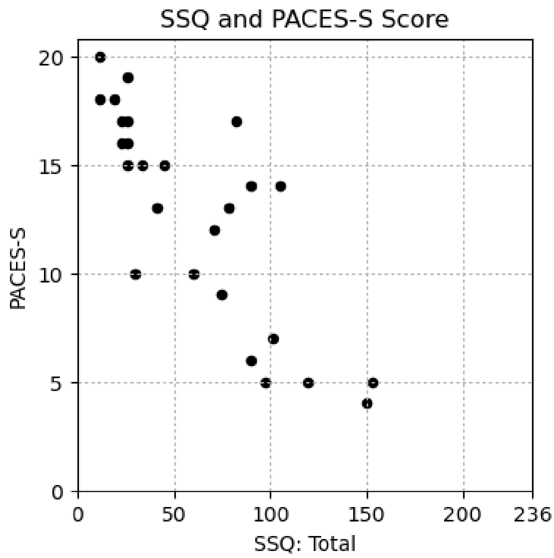
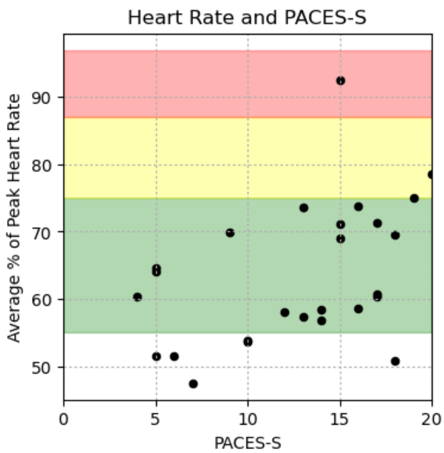
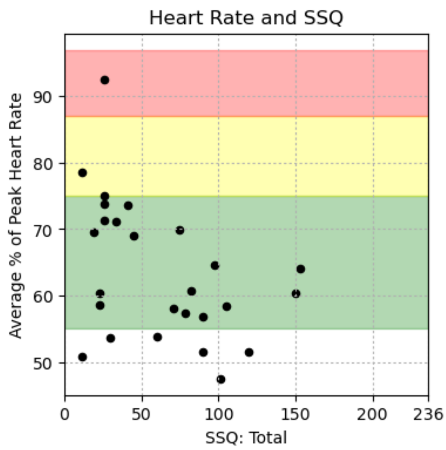


Figure 4.6: SSQ and PACES-S scores

4.2.2 Heart Rate



(a) Heart rate and PACES-S score



(b) Heart rate and total SSQ score

Figure 4.7: Heart rate, PACES-S and SSQ scores

Figure 4.7 shows how the heart rate varies both with the PACES-S score and the SSQ score. Figure 4.7a shows the slight positive correlation between the PACES-S score and heart rate, whereas fig. 4.7b shows that heart rate tends to decrease as SSQ increases.

Recall from table 4.1 that the red zone corresponds to high cardio intensity, yellow implies a moderate cardio intensity and the green is a low cardio intensity zone. As is evident from fig. 4.7, very few participants reached the moderate and high intensity exercise zones. Most of the benefits to the cardiovascular system is gained in moderate to high intensity exercise [46, p. 510]. This means that if the device is regularly used at the intensity that most of the players used it at, the improvements to physical health will not be as good as with more intense exercise.

As was established at the start of the analysis performed for this research question, the ability for users to achieve an elevated heart rate during the use of the device is a crucial. The presence of cybersickness may act as a limiting factor for users to reach elevated heart rates. As illustrated in fig. 4.7b, the inverse relationship between heart rate and SSQ scores suggests that cybersickness may inhibit users from fully engaging in the exergame and experiencing its intended health benefits.

Given these findings, it becomes evident that the reduction or elimination of cybersickness is of high importance. By addressing cybersickness effectively, users can be provided with a more optimal environment to fully immerse themselves in the exergame and potentially achieve the desired elevation in heart rate. This, in turn, can contribute to a more positive and rewarding experience, which enhances the overall user satisfaction and the potential health benefits derived from the VR wheelchair simulator.

4.2.3 Intuitive Gameplay

Realistic and intuitive controls might contribute to a better user experience. Users will feel a higher level of immersion and fun if they do not feel that they are fighting against the controls of the game. The exergame platform went through three iterations, trying different data processing strategies for every iteration. Did the user feel that the player controls were sufficiently realistic and intuitive in the final version of the device?

Figures 4.8–4.10 show word clouds over the 20 most common words from the free-form feedback section for the three respective testing rounds. As shown in fig. 4.10, control-related words are far less frequent than in figs. 4.8 and 4.9. This was also evident from the feedback given in real-time by participants during the play time. When testing device versions 1 and 2, participants would frequently highlight the controller as being the source of their discomfort, whereas in version 3 the comments from participants would range from the in-game textures to the temperature of the room they were in.

The infrequent commenting on the player controls in the final version of the device suggest that the controls may feel sufficiently realistic and intuitive. Note that this intuition is extrapolated based on discussions with participants and the author's domain expertise. It is therefore difficult to exactly pinpoint whether this intuition is correct, as ideally this conclusion would be drawn based on more numerical data.

Figure 4.8: Word cloud for round 1 of testing

Word	Relative Frequency
turning	0.054
sensitive	0.024
less	0.024
sick	0.024
little	0.024

Table 4.8: Top 5 words and their relative frequencies for round 1 free-form feedback

Figure 4.9: Word cloud for round 2 of testing

Word	Relative Frequency
turning	0.060
time	0.045
better	0.045
think	0.045
felt	0.030

Table 4.9: Top 5 words and their relative frequencies for round 2 free-form feedback

Figure 4.10: Word cloud for round 3 of testing

Word	Relative Frequency
felt	0.023
vr	0.023
like	0.019
think	0.015
game	0.015

Table 4.10: Top 5 words and their relative frequencies for round 3 free-form feedback

4.3 Characteristics of Cybersick Individuals

The final research question aims to identify common characteristics among individuals who experience cybersickness in response to the exergame platform and examine how these traits differ from those who do not experience cybersickness. To get as good grounds for comparison as possible, only data collected form the final version of the device, with $n = 26$, is used in this section.

> **RQ3:** What are the characteristics of individuals who experience cybersickness in response to the exergame platform, and how do they differ from those who do not experience cybersickness?

Upon examining fig. 4.11, it becomes evident that the most influential factor differentiating individuals who experience cybersickness might be their self-reported susceptibility to motion sickness. Individuals who are prone to motion sickness tend to have higher SSQ scores. There also seems to be a correlation between gender and SSQ scores, with female participants generally scoring higher than their male counterparts. An analysis of participants' VR habits in relation to their SSQ scores will be conducted, although fig. 4.11 does not seem to suggest so. Nevertheless, it is still worth investigating whether the cybersickness symptoms might be mitigated through increased VR exposure and experience.

It is important to note that other correlations observed in fig. 4.11 are likely to represent causal relationships. For instance, it is plausible that a high degree of cybersickness could influence an individual's enjoyment, in-game movement speed, and heart rate. However, exploring the relationship between user movement speed and their cybersickness score remains valuable, as this metric does not rely on sensor input or self-reporting.

Correlation coefficients and p-values for SSQ: Total

	r	p
Gender	0.413150	0.035921
MS prone	0.555038	0.003249
VR habits	-0.051497	0.802715
Cardio habits	0.074826	0.716392
Height	-0.238277	0.241116
Age	0.047521	0.817684
PACES-S	-0.816608	0.000000
Play Time (%)	-0.480345	0.013003
$\%HR_{peak}$	-0.430399	0.028178
Avg EDA	-0.003171	0.987733
Avg Movt Speed	-0.565669	0.002597
Avg Turn Speed	-0.513710	0.007268

Figure 4.11: Pearson's correlation coefficient and two-sided t-test p-values for SSQ score

4.3.1 Motion Sickness Susceptibility

In the post-test questionnaire (appendix F), participants were asked a yes/no question about whether or not they were prone to experiencing motion sickness. This self-assessed susceptibility to motion sickness seems to be a strong indicator of the degree of cybersickness symptoms the user will experience.

Figure 4.12 shows that the majority of participants that self-reported a susceptibility to motion sickness score far higher total SSQ than that of those who are not prone to experiencing motion sickness. From the standard deviations of each groups, given in table 4.11, it is clear that the data is very spread out for both groups, however, the group that answered ”no” to the question seem to score an acceptable SSQ score, suggesting that the device may be fit for use if a person is not prone to experiencing motion sickness.

This also fits with existing literature in the field, where motion sickness susceptibility has by some been referred to as the primary driver of cybersickness [51].

Motion Sickness Susceptibiltiy and Total SSQ Score Statistics						
MS Prone?	Count	Median	Mean	SD	Min	Max
Yes	11	89.76	88.74	37.07	41.14	153.34
No	15	26.18	42.39	34.73	11.22	119.68

Table 4.11: Total SSQ Score statistics, grouped by motion sickness suceptibility

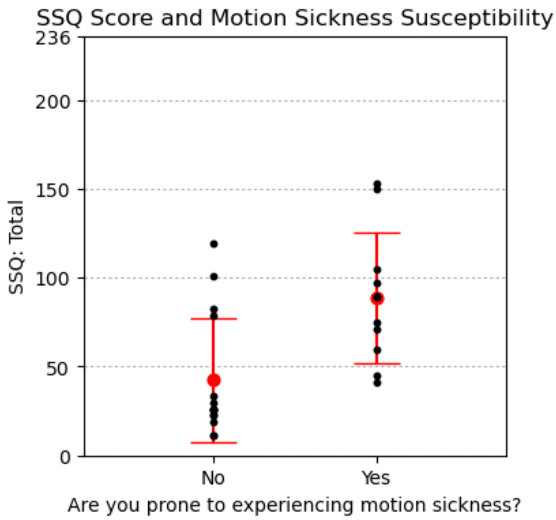


Figure 4.12: SSQ and motion sickness suceptibility

4.3.2 Play Mode Preference

The post-test questionnaire (appendix F) featured the following question: "Would you prefer to play an exercise game like this with or without a VR headset?" As shown in table 4.12, the majority of people (12) that participated in the study answered that they would prefer to play it on a normal screen (monitor). Most participants that would have preferred to use a monitor had a high SSQ, with a median SSQ score of 86.02.

Play Mode Preference and Total SSQ Score Statistics						
Play Mode Preference	Count	Median	Mean	SD	Min	Max
Don't Know	5	22.44	22.44	7.00	11.22	29.92
Monitor	12	86.02	90.38	37.12	33.66	153.34
VR Headset	9	26.18	46.13	33.82	11.22	104.72

Table 4.12: Total SSQ Score statistics, grouped by play mode preference

Individuals who answered "don't know" had, somewhat suprisingly, the best SSQ scores as shown by them having both the lowest mean and median scores in table 4.12. When running the tests, these individuals often expressed that they found the VR headset relatively unproblematic, but that since they did not get the opportunity to try the game using a monitor, they were not sure which one they would prefer.

Participants that would prefer to use a VR headset for the exergame platform totalled 9, with their median SSQ score being 26.18, which is very different from the mean of 46.13. An important factor to consider here, is the fact that most participants were students at NTNU, meaning that they are likely to have an above average interest in technology. Many participants, even if they experienced a lot of cybersickness, expressed that they found the concept cool and that they found the technology exciting. It is therefore not unreasonable for some participants to have answered that they would prefer the VR Headset because they saw the promise in the technology and believed that the source of their cybersickness might be fixed with some extra work.

In addressing RQ3, it can be concluded that individuals who experience a lot of cybersickness in response to the exergame platform tend to prefer the thought of using a monitor over using a VR headset. On the other hand, those with lower SSQ scores were more likely to prefer the VR headset. Additionally, the demographic of NTNU students, who likely possess an above-average interest in technology, should be considered when interpreting these findings. Some participants may have chosen the VR headset despite experiencing cybersickness, given their recognition of the technology's potential and their belief that the issues causing cybersickness could be resolved with further development. Because of this, a more realistic insight might be gained if the sample are more diverse and outside of the university sphere. In summary, users who experience cybersickness are more likely to prefer the thought of playing the exergame using a monitor, whereas less cybersick individuals are more likely to either be unsure or prefer the VR headset.

4.3.3 VR Gaming Experience

Is it possible that the amount of cybersickness symptoms that users experience might be reduced with more frequent exposure to VR? Most participants answered that they "Never" or "Irregularly" played VR games. Although efforts were made to recruit participants with more VR experience, the amount of data collected on individuals with more VR experience remains too sparse to draw any meaningful conclusions. Judging from fig. 4.13, there does not seem to be any indication of that the cybersickness is less severe for habitual VR users. Statistics summarized in table 4.13 seem to further support this finding, with the data being generally very spread out, and both the means and medians neither consistently increasing nor decreasing.

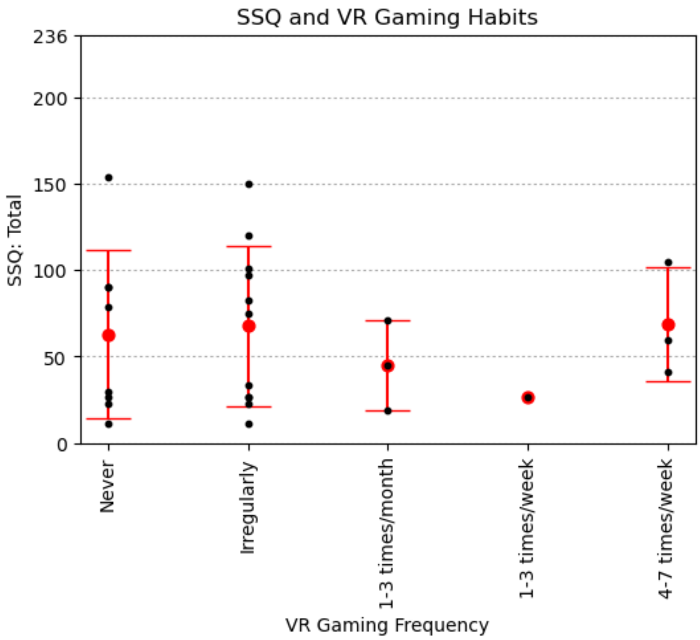


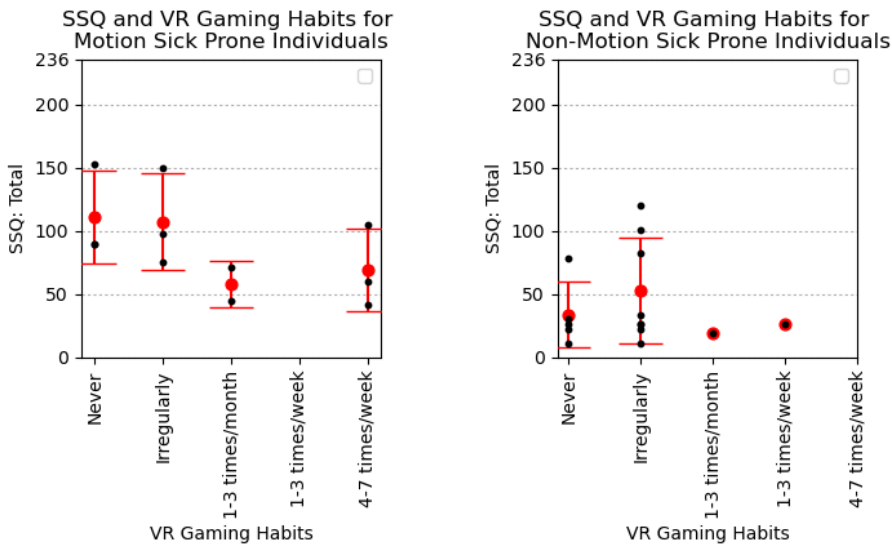
Figure 4.13: Total SSQ score and VR experience

VR Habits and Total SSQ Score Statistics						
VR Gaming Frequency	Count	Median	Mean	SD	Min	Max
Never	8	54.23	62.65	48.71	11.22	153.34
Irregularly	11	74.80	67.66	46.37	11.22	149.60
1-3 times/month	3	44.88	44.88	26.18	18.70	71.06
1-3 times/week	1	26.18	26.18	N/A	26.18	26.18
4-7 times/week	3	59.84	68.57	32.68	41.14	104.72

Table 4.13: VR Gaming Frequency and Total SSQ Statistics

As established in section 4.3.1, motion sickness susceptibility seemingly has an impact on the amount of cybersickness an individual feels. By separating the data points between those that are susceptible to motion sickness (fig. 4.14a) and those who are not (fig. 4.14b), a somewhat clearer picture emerges. Generally, individuals who played VR games more frequently had a lower SSQ score. For MS prone participants, the SSQ scores for the collected data were lower both in mean and median for participants that played VR games more than 1-3 times per month, which can be seen in table 4.14. Non-MS prone participants also saw a decrease in the SSQ scores although this improvement was moderate. Since there is so little data on non-MS prone participants with more VR experience, it is uncertain whether this improvement is representative.

These data might be in line with past research on participants' acclimation to VR environments. One study found that repeated exposure to VR experiences reduced the prevalence and severity of cybersickness, regardless of if the exposure happened once daily or once weekly [48]. Another study also supports that simulator sickness is at least partially associated with the participant's level of experience with the simulated environment [59].



(a) SSQ across VR experience for motion sick susceptible individuals

(b) SSQ across VR experience for non-motion sick susceptible individuals

Figure 4.14: Total SSQ score and VR experience separated by motion sickness proneness

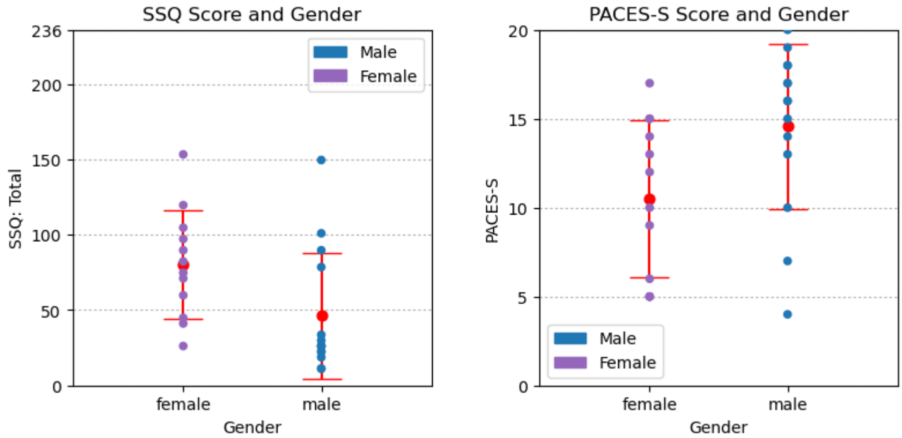
VR Habits and Total SSQ Score Statistics							
MS Prone?	VR Gaming Frequency	Count	Median	Mean	SD	Min	Max
Yes	Never	3	89.76	110.95	36.71	89.76	153.34
	Irregularly	3	97.24	107.21	38.38	74.80	149.60
	1-3 times/month	2	57.97	57.97	18.51	44.88	71.06
	1-3 times/week	0	-	-	-	-	-
	4-7 times/week	3	59.84	68.57	32.68	41.14	104.72
No	Never	5	26.18	33.66	26.05	11.22	78.54
	Irregularly	8	29.92	52.83	41.57	11.22	119.68
	1-3 times/month	1	18.70	18.70	-	18.70	18.70
	1-3 times/week	1	26.18	26.18	-	26.18	26.18
	4-7 times/week	0	-	-	-	-	-

Table 4.14: VR Gaming Frequency and Total SSQ Statistics

Despite research suggesting that increased exposure to VR might reduce cybersickness, it is also crucial to point out that there may be some confounding factors that affect the data. It might be reasonable to assume that people who play VR games more frequently are less likely to be people who experience large amounts of cybersickness when playing. Otherwise, why would they keep playing? For the collected data, it is therefore not possible to draw any conclusion solely based on this data. A new study where the same participants test the game multiple times might be beneficial to more effectively address this issue.

4.3.4 Gender Differences

In the data, there seems to be a large disparity in both the PACES-S and SSQ scores achieved by men and women. This disparity is seen in fig. 4.15, where the data points have been colored according to the participants' gender. The data displayed in the graphs are also summarized in tables 4.15 and 4.16, where the median and mean SSQ scores for women are significantly higher than that of men. Correspondingly, women score lower on the PACES-S. The spread of the data is consistent for both genders.



(a) SSQ scores and gender **(b)** PACES-S scores and gender

Figure 4.15: Gender distribution of scores

Total SSQ Score statistics						
Gender	Count	Median	Mean	SD	Min	Max
Female	12	78.54	80.41	35.82	26.18	153.34
Male	14	26.18	46.22	41.69	11.22	149.60

Table 4.15: Total SSQ statistics by gender

PACES-S statistics						
Gender	Count	Median	Mean	SD	Min	Max
Female	12	11.00	10.50	4.44	5.00	17.00
Male	14	16.00	14.57	4.65	4.00	20.00

Table 4.16: PACES-S statistics by gender

Is there any way to explain for this disparity? Upon further inspecting the distribution of individuals who are and are not prone to experiencing motion sickness, the answer is still inconclusive. Table 4.17 shows that for the female participants, only three reported that they generally did not experience motion sickness, and nine reported that they did. Nevertheless, the median score for the three women that are not prone to experiencing motion sickness is 82.28, which is still far higher than the median SSQ score for their non-motion sick male counterparts in table 4.18 which is 26.18. The number of non-motion sick women is so small that it is difficult to say whether this discrepancy simply is an ”unfortunate” sampling of the non-motion sick prone women or whether the discrepany indicates a trend.

Twelve of the men that participated in the tests were not prone to experiencing motion sickness, and two were, as shown in table 4.18. The total SSQ scores of the men that answered ”no” to the question is generally very good. The two men that answered ”yes” to the question had a SSQ scores that were significantly higher than that of the women who also answered ”yes”. Because only two men answered ”yes”, it is not possible to determine if this is simply chance, or if men who are prone to experiencing motion sickness do indeed feel even more cybersickness symptoms than women who are also prone to experiencing motion sickness.

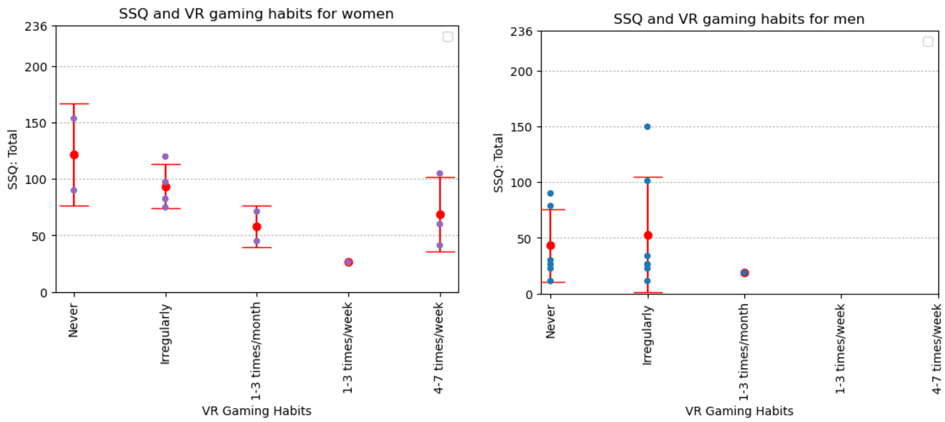
Female Motion Sickness Susceptibiltiy and Total SSQ Score Statistics						
MS Prone?	Count	Median	Mean	SD	Min	Max
Yes	9	74.80	81.86	34.66	41.14	153.34
No	3	82.28	76.05	47.06	26.18	119.68

Table 4.17: Female susceptibility to motion sickness and the corresponding total SSQ score

Male Motion Sickness Susceptibiltiy and Total SSQ Score Statistics						
MS Prone?	Count	Median	Mean	SD	Min	Max
Yes	2	119.68	119.68	42.31	89.76	149.60
No	12	26.18	33.97	27.32	11.22	100.98

Table 4.18: Male’s susceptibility to motion sickness and the corresponding total SSQ score

In section 4.3.3, there was some evidence to suggest that the cybersickness symptoms may reduce with more regular exposure to VR experiences. In fig. 4.16a, the women with a lot of VR experience have a lower mean SSQ score than women who never or rarely play VR games. For males, shown in fig. 4.16b, there are not enough samples for more experienced individuals to say if this is also the case for men. Therefore,



(a) SSQ and VR experience for women **(b)** SSQ and VR experience for men

Figure 4.16: SSQ and VR habits for men and women

Possible explanations for gender differences

There is an abundance of literature that has investigated the matter of gender differences and cybersickness symptoms. Some research has suggested that when using the self-report questionnaires, men tend to under-report their symptoms when compared to women [60]. Other literature suggests that women might be more susceptible to motion sickness in general, men play more games or that VR headsets simply are not made to fit women. This is further described in the following paragraphs.

Research has shown that women are, in general, more susceptible to experiencing motion sickness [51] than men are. Women's proneness to experiencing nausea and motion sickness has also been shown to vary with the menstrual cycle [61], [62]. Other studies have postulated that women might become more nauseated from VR experiences because they have a wider field of view [29].

People who have more experience with games in general tend to perform better virtual environments [63], particularly if they have played a lot of first person shooter (FPS) games. This improved performance might allow them to move more efficiently in virtual enviroments which might influence the degree of cybersickness they might feel [28, p.54]. Surveys have found that the vast majority of people who play FPS games are males [64]–[66]. For this thesis, no data was collected on participants' gaming habits outside of VR, but the difference in gaming habits, particularly for FPS games, might explain some of the difference in SSQ scores.

A more recent study pinpoints the gender differences down to the VR headset itself, finding that the driving factor for the gender difference is the way the VR headset is configured [67]. Each VR headset is made for a certain range of distances between the pupil of both eyes, also called interpupillary distance (IPD). This study claims that a non-fit of a person's IPD is the primary driving factor for gender differences, as women generally have a smaller IPD than men. Adult women's IPD typically varies from 51-74.5mm with a mean of 61.7mm, whereas adult men's IPD typically ranges from 53-77.5mm with a mean of 64mm [67].

The IPD ranges for the VR headset used in the experiments, the Meta Quest 2, are shown in table 4.19. The headset may be adjusted to three discrete levels. Although no record of the IPD for the participants were done, another study found that the IPD mismatch for the Meta Quest 2 tends to be larger for women (M=4.4 mm, SD=2.7) than for men (M=3.0mm, SD=1.86) [68]. Another source of an IPD mismatch is that participants were encouraged to ”adjust the headset so it feels good” with little additional guidance. For less experienced VR Headset participants, this might have lead to them adjusting the lens spacing to the incorrect level. Many participants also did not adjust the lens spacing at all.

IPD Range	Lens Spacing Setting
61mm or smaller	1 (narrowest, 58mm)
61mm to 66 mm	2 (middle, 63mm)
66mm or larger	3 (widest, 68mm)

Table 4.19: Interpupillary distance settings for the Meta Quest 2

4.3.5 In-game Performance

As shown in fig. 4.17, there seems to be some relationship between the user’s average movement speed and the degree to which they experience cybersickness. Of course, this relation would only hold for games whose sole purpose is to move around, which is the case for the game that was played in this study. The relationship seems to be significant enough to conclude that individuals who experience cybersickness tend to move slower in the game, as is evident from the downwards-sloping trend in fig. 4.17.

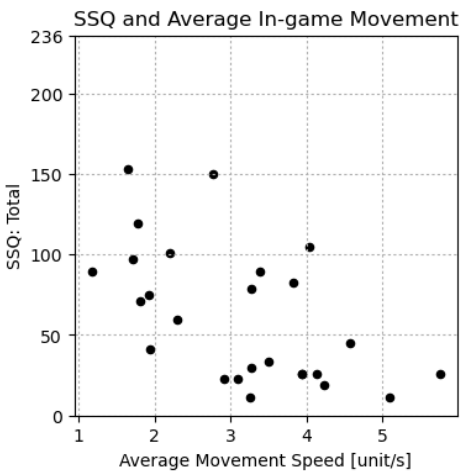


Figure 4.17: SSQ and average in-game movement speed

5

Summary of Results

This chapter contains a summary of the data collection and analysis performed in this thesis. The observations and main synthesis about the data in regards to the research question are done in chapter 4. This chapter summarizes the key findings and their implications.

5.1 Summary of Data Collection

The data collection process was desribed in-depth in chapter 3, but a brief summary is given in this section.

The exergame platform has undergone two revisions, resulting in three distinct device versions. Each version of the device was tested, with participants being recruited from the author's social networks and also using posters. Based on the feedback from the participants, the device was iterated upon in an attempt to fix the problems that users highlighted. The device underwent three iterations as early tests for the third and final device version seemed sufficient. The number of participants that tested device version 1 was 6, device version 2 was tested by 5 people while the final and third version of the device was by 26 participants. The third version of the device was tested by the most participants as the goal was to be able to give meaningful insights about the state of the device and more effectively answer RQs 2 and 3. Additionally, using a larger sample size for the final version of the device will give better grounds for comparisons by later studies on the same or similar platforms.

Data was collected in three different ways: through sensors on the body, through logging metrics of the users' in-game performance, and through a questionnaire. A specific checklist of what each trial entailed is given in appendix G. The measurements that were done on the body were heart rate sensing using a Polar H10 heart rate belt along with electrodermal activity and temperature sensing done on the Empatica 4. From the game, a log of the in-game quantities like total turning and total movement done throughout the experiment as well as the user's best lap time was recorded. Finally, participants answered a questionnaire (appendix F) that contained many different items, like their age, motion sickness susceptibility, VR gaming experience and most importantly, their answers to the

Short Physical Activity Enjoyment Scale (PACES-S) and the Simulator Sickness Questionnaire (SSQ).

5.2 Results by Research Question

The following sections summarize the findings from the data analysis chapter. Conclusions and findings about RQ1 are given in section 5.2.1, findings about RQ2 are given in section 5.2.2 and findings about RQ3 are given in section 5.2.3.

5.2.1 Research Question 1

The exergame platform's impact on cybersickness and enjoyment was evaluated to address RQ1. The analysis revealed that the average user's playtime increased slightly from round 1 to 2 and significantly from round 2 to 3, while the severity of cybersickness symptoms also increased steadily across rounds. This finding suggests a need to further identify and address factors contributing to cybersickness. The SSQ scores for each round showed that attempted improvements on the device did not substantially change the degree of cybersickness experienced by users. It was also observed that individuals less prone to motion sickness experienced lower levels of cybersickness while using the exergame platform, highlighting the importance of obtaining a representative sample of users.

Regarding enjoyment, the analysis of PACES-S scores revealed a decrease in enjoyment as the device was refined. This counterintuitive finding, along with participants' verbal feedback, suggests that factors other than the device itself may be more influential to user enjoyment, such as the game or VR experience. As a result, there is the need to consider both the game design and the VR environment to enhance user satisfaction and minimize potential negative effects.

In conclusion, the way the wheels' rotational speeds are processed in the exergame platform might not be the most impactful part of players' enjoyment of the concept nor the level of cybersickness that they feel.

5.2.2 Research Question 2

For RQ2, the analysis was focused on identifying factors contributing to a good user experience in the VR wheelchair simulator and their relationship to the design and implementation of the exergame platform. The analysis primarily considered PACES-S in relation to heart rate and SSQ, using data from the final testing round with $n = 26$ participants.

A strong inverse relationship between the SSQ and PACES-S scores was found, suggesting that the absence of cybersickness symptoms significantly contributes to a positive user experience. Heart rate appeared to be positively correlated with PACES-S score, while negatively correlated with SSQ score. These findings indicate that cybersickness may act as a limiting factor for users to achieve elevated heart rates when playing the exergame. The ability to achieve an elevated heart rate is essential for its intended health benefits. Addressing the cybersickness problem effectively is crucial for providing users with an optimal experience, allowing them to fully immerse themselves in the game while simultaneously achieving the desired elevation in heart rate.

Additionally, qualitative analysis of free-form feedback across the three testing rounds revealed a shift in user comments from focusing on control-related issues to other aspects of the experience. This suggests that the controls in the final version of the device were perceived as sufficiently realistic and intuitive, contributing to enhanced user experience.

In summary, the results from the data analysis shows that minimizing cybersickness symptoms, providing an environment conducive to elevated heart rates, and offering realistic and intuitive controls are important factors for ensuring a good user experience in the VR wheelchair exergame platform.

5.2.3 Research Question 3

RQ3 aims to find traits that separates participants who did experience cybersickness from those who did not. The full analysis was done in section 4.3. Participants' self-reported motion sickness susceptibility, play mode preference, VR gaming experience, gender and in-game performance were analysed in the pursuit of finding features common to those who experienced cybersickness.

The features that seemed to be the primary drivers of the participants' SSQ scores were motion sickness susceptibility (section 4.3.1) and gender (section 4.3.4). It is not possible to determine which of motion sickness susceptibility or gender is the primary and secondary driver, as 9 out of 12 women reported to be susceptible to motion sickness whereas only 3 out of 14 men reported likewise. Research on this problem is inconclusive, with some studies attributing the differences in response to women being more prone to motion sickness [51], [61], [62], whereas other studies attribute the gender differences to the fact that VR Headsets are made to fit most men but not all women [67].

Another feature that was common to those who experienced a lot of cybersickness, is the fact that they were unable to move fast in-game. This indicates that they are unlikely to get the full benefit of the exergame platform in terms of physical exercise and overall enjoyment. This is supported by the observed negative correlation between the average in-game movement speed and SSQ scores.

In analysing users' play mode preference and cybersickness symptoms, a clear relationship was found. Participants with high SSQ scores, indicative of substantial cybersickness, tended to prefer playing on a monitor, while those with lower SSQ scores were more likely to prefer the VR headset or be unsure of their preference. It is important to consider the demographic of the study, as a majority of participants were NTNU students, who may have an above-average interest in technology. This factor could have influenced some participants to choose the VR headset despite experiencing cybersickness, due to their belief in the potential of the technology and the possibility of addressing cybersickness-related issues with further development. To obtain a better understanding of user preferences, future research may benefit from a more diverse sample beyond the university setting.

Participants' past exposure to VR experiece shows some evidence that the cybersickness symptoms might be reduced through increased exposure to VR. The majority of participants reported "Never" or "Irregularly" playing VR games, and the limited data on individuals with more VR experience did not show a clear trend indicating reduced cybersickness severity for habitual VR users. However, when separating the data points based on motion sickness susceptibility, it was observed that individuals who played VR games more frequently generally had lower SSQ scores. For motion sickness-prone participants, both the mean and median SSQ scores were significantly lower for those who played in VR games more than 1-3 times per month. Non-motion sickness-prone participants also demonstrated an improvement in SSQ scores, albeit moderate, with increased VR experience. Due to the lack of data on more experienced VR users, it is uncertain whether this improvement is truly representative. In summary, while there is some indication that suggests that increased exposure to VR experiences might lessen cybersickness symptoms further research with a larger and more diverse sample is necessary to draw definitive conclusions.

6

Methodological Considerations and Further Work

The previous chapters of this thesis, particularly the Data Analysis (chapter 4) and the Results (chapter 5), undertook the task of synthesizing the data, answering the research questions and connecting the findings with existing academic knowledge. This chapter examines the wider implications of the results, both in the context of current understanding and potential applications. The following sections contain discussions of the broader applicability of the results, the potential limitations that may affect the interpretation of the results as well as suggestions for further study.

6.1 Applicability of results

One key finding of this thesis is the crucial role that cybersickness has in shaping the overall user experience. For VR exercise applications, it is crucial to focus on reducing cybersickness as this seems to limit participants from achieving an elevated heart rate in a navigation-based VR game setting. The negative correlation between SSQ and average in-game speed further supports the claim that cybersickness impedes players from fully benefiting from the exergame platform in terms of physical exercise and enjoyment. These findings can inform the design and development of similar exergame platforms.

The presented results highlight the importance of individual user preferences in a VR experience. Different users have varying degrees of motion sickness susceptibility, which greatly impacts their interaction with VR-based exergames. The development of adjustable features, for example by creating a game that would work both with or without using a VR headset, could significantly enhance the accessibility and appeal of exergame platforms like the one that was created in this thesis.

By taking into consideration the results presented in this thesis, insights might be formed that may aid in the development of more accessible, engaging and rewarding VR and/or exergame experiences. While the findings are most directly applicable to similar projects, they also hold potential implications for the wider field of VR design.

6.2 Limitations

In any study, there are a number of limitations to the research design, methodologies and participant selection that may impact the interpretation and generalizability of the findings. The study conducted in this thesis is no exception, with several limitations that need to be acknowledged in understanding its implications. These include sample size and diversity of the participant pool, the duration of the playtest and the methods for data collection. The following sections provide an in-depth explanation of these limitations and how they impact the findings of this study.

6.2.1 Sample Size and Diversity

As was first mentioned in chapter 3, recruitment was done through social networks and posters around the NTNU university grounds. This means that most of the participants will be from a very specific demographic group, being limited in age, interests and nationality. This is an unfortunate but hard-to-mitigate side effect, as substantially more time would have had to be spent in order to recruit participants from outside of the university sphere.

An unfortunate fact about the participants' sample population is that although the technology is meant for wheelchair users, only one individual had used a wheelchair before. This was explained in section 3.6.3, and certainly would have been done if the initial results of the device were satisfactory.

Because of the limited diversity and sample size of the participants, it is not possible to say whether the results apply to the general population and particularly wheelchair users.

6.2.2 Duration of Playtest

Due to the low rate of completion for the first testing round, the duration of the game time was reduced from 15 to 10 minutes in round 2 and 3. As described in section 3.6.3, participants' cybersickness score tends to peak in the 10-20 minute range. As such, testing users with a play time of 10 minutes is likely to not be representative of realistic use, as a cardio training session might last for far longer.

6.2.3 Data Collection Methods

The methods used for data collection have some inherent limitations. The analysis and conclusions drawn thereupon relied heavily on self-report measures, specifically the Simulator Sickness Questionnaire (SSQ) and the Short Physical Activity Enjoyment Scale (PACES-S). These tools are widely used but are not without their shortcomings. Self-report questionnaires are inherently subjective and can be influenced by a variety of factors such as an individual's mood, ability to recall information accurately or understanding and interpretation of the question. Therefore, the findings through the use of these subjective metrics will not be as strong as for findings that might derived from physiological data.

The study conducted in this thesis had no control group, and as mentioned in section 3.1.1, it might be wrong to assume that the baseline for users is a 0 in the SSQ scoring. In order to get a better insight into what effect the navigation method had on the user scoring, it might have been useful to use a control group that used a different navigation method such as discrete movement methods such as teleportation.

6.3 Further work

The research that was done in this thesis yielded significant insights into the development and user experience of the VR exergame platform for wheelchair users. As is often the case with early research and development, a number of directions for further work and improvement was exposed. These directions for further work will not only serve to address the limitations of this thesis, but also aim to enhance the potential benefits of the exergame platform.

6.3.1 Evaluate Different Types of Games

In addressing RQ1, it was found that the method of signal processing within the game controller has a minimal impact on the levels of cybersickness and enjoyment experienced by the user. This outcome challenges the initial hypothesis and indicates that the manipulation of rotational speeds in the exergame platform may not be the determining factor in mitigating cybersickness or enhancing user enjoyment.

Given these results, it may be more beneficial to shift the focus towards exploring different types of game modes. It is possible that game design aspects such as genre, narrative, mechanics, and graphics may have a more significant influence on the user experience, enjoyment and symptoms of cybersickness.

For instance, exploring genres outside of navigation-based games, such as rhythm games, could present unique dynamics that alter user interaction and experience. Similarly, incorporating different game mechanics, such as object manipulation or multi-player elements, may provide varying levels of challenge and engagement that impact user enjoyment and the potential for exercise.

As such, future research could involve the development and testing of various game modes, examining their impact on user experience in terms of both enjoyment and cybersickness. These studies could employ user feedback to identify which game features are most preferred and least likely to induce cybersickness. This could inform the design of future exergames, ensuring they are enjoyable, engaging, and comfortable for users, which might enhance their effectiveness as tools for physical activity and fitness.

6.3.2 Compare the VR Exergame to Non-VR Exergames

The exploratory research and development done in this thesis has laid the groundwork to interface the developed exergame platform with other applications. With some additional work, it will be possible to have the exergame platform interact not only with games, but also with other types of exercise applications.

An interesting direction for future investigations could be the integration of the exergame platform with popular non-VR applications such as Zwift. Zwift is a fitness app designed for runners and cyclists that enables users to play together and compete with friends using indoor bicyles or treadmills. This could provide an exciting and motivating environment for wheelchair users, offering a sense of camaraderie and competition which might help them stick to a training regimen.

It could, for example, be useful to see if by using the exergame platform and Zwift will lead to a higher PACES-S score and heart rate than was achieved in the VR exergame. Since a VR headset is quite expensive, this area of further work holds a lot of potential as it is a lower-cost alternative to playing exergames. If users are able to achieve similar or higher PACES-S scores and heart rate levels, it might be better to focus research efforts on this area rather than VR exergames.

6.3.3 Conduct a Study on the Intended Users

An important limitation that was discussed in section 6.2.1 is the fact that the intended target users, namely wheelchair users, were not recruited for the study. While the insights gained from able-bodied individuals certainly is valuable, they cannot entirely predict the responses, needs and experiences of wheelchair users.

Testing with wheelchair users is of utmost importance not only to the accessibility and practicality of the platform, but also to measure its effectiveness and user enjoyment under real-world conditions. The unique experiences, preferences and challenges that wheelchair users encounter in daily life may significantly influence how they interact with and perceive the VR exergame platform.

Wheelchair users may have varying degrees of upper body strength, physical stamina and mobility constraints. All of these factors may impact their interaction with the exergame platform. Wheelchair users could as such provide important feedback on elements like the platform's comfort, its realistic simulation of wheelchair movements and the suitability of the game's controls and mechanics for long-term use.

Conducting a study with wheelchair users would thus allow for further refining the design and implementation of the exergame platform in a way that will better cater to their needs and preferences. Feedback from wheelchair users could lead to further improvements and modifications that might not have been considered or anticipated based on the feedback from able-bodied users. Including wheelchair users in the testing and development process can ensure the exergame platform is more likely to succeed in its goal of creating an engaging, enjoyable and beneficial exercise tools for the intended users.

6.3.4 Further Improvements to the Device Itself

Throughout the course of the study, an issue that is critical to user experience was uncovered. The Bluetooth connection between the device and the computer would often times be interrupted, which disrupted the smooth operation of the exergame platform. To fix this issue, the device would have to be restarted which resulted in users not being able to give input for about 5 seconds. Attempts to mitigate these disturbances, such as enabling flight mode and disabling Bluetooth on nearby phones, seemed to somewhat alleviate this problem with disconnections happening less frequently.

The presence of this connection instability raises concerns about the device's performance, particularly if this platform is to be rolled out for use by a wider population. Since the author always was present to reset the device whenever this happened, this issue was deemed acceptable for the study but will be problematic if users have to take off their VR headset to restart the device themselves. Given the immersive nature of VR games, connectivity disruptions can lead to jarring user experiences that may exacerbate cybersickness symptoms or undermine enjoyment and engagement with the game. Prior to rollout of any final product, this connection issue needs to be thoroughly addressed and resolved.

The Bluetooth connection problem likely stems from either hardware-related issues, such as a weak antenna, or software-related issues such as ineffective handling of signal interference. Extensive efforts were made to troubleshoot the problem but no clear solution was found. Further work should therefore focus on isolating and rectifying the source of this problem through rigorous testing and a potential redesign of the device's connectivity components. This might involve exploring alternative hardware components or refining the software module for connectivity management.

7 Conclusion

The purpose of this thesis has been to develop and evaluate a new device that enables wheelchair users to play exergames in VR. The exergame platform was primarily evaluated in terms of its potential to captivate users. The influence of the wheelchair wheels' rotational speeds processing on the user experience in the VR exergame platform was investigated. The thesis has particularly focused on users' cybersickness symptoms and their sense of enjoyment. Additionally, the thesis aimed to identify factors that contribute to a good user experience, and to understand the characteristics of individuals who experience cybersickness.

Data was collected in three separate rounds with a different rotational speed processing configuration for each round. The number of participants for each test round was 6, 5 and 26. The most significant data was collected through self-report questionnaires. Sensor data such as heart rate and electrodermal activity, along with in-game data such as cumulative distance moved, was also collected and analysed to answer the research questions.

The findings, listed per research question in chapter 5, show that the signal processing of the exergame platform has seemingly little impact on the degree of cybersickness and user enjoyment. While the results concluded that the user experience is likely best when the controls feel realistic and intuitive, other efforts such as changing the gameplay might be better at alleviating the cybersickness problem. Cybersickness was found to have a strong inverse relationship to enjoyment and might inhibit participants' ability to achieve a moderate to high exercise intensity level. Participant traits such as self-reported motion sickness susceptibility and gender were strongly correlated with the amount of cybersickness they felt.

The results have provided valuable insights about the exergame platform but the need for further research is also evident. Further work should seek to explore different types of VR games, compare VR exergames to non-VR alternatives, conduct studies with wheelchair users, and possibly address technical issues related to the connectivity of the device.

Bibliography

[1] V. Anneken, A. Hanssen-Doose, S. Hirschfeld, T. Scheuer, and R. Thietje, "Influence of physical exercise on quality of life in individuals with spinal cord injury," *Spinal cord*, vol. 48, pp. 393–9, Oct. 2009. DOI: 10.1038/sc.2009.137.

[2] A. Lannem, M. Sørensen, K. Frøslie, and N. Hjeltnes, "Incomplete spinal cord injury, exercise and life satisfaction," *Spinal cord*, vol. 47, pp. 295–300, Nov. 2008. DOI: 10.1038/sc.2008.117.

[3] G. Kavetsos, "The impact of physical activity on employment," *The Journal of Socio-Economics*, vol. 40, no. 6, pp. 775–779, 2011, ISSN: 1053-5357. DOI: https://doi.org/10.1016/j.socec.2011.08.011. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1053535711000990.

[4] P. Katzmarzyk and I. Janssen, "The economic costs associated with physical inactivity and obesity in canada: An update," *Canadian journal of applied physiology = Revue canadienne de physiologie appliquée*, vol. 29, pp. 90–115, Mar. 2004. DOI: 10.1139/h04-008.

[5] *Tall og fakta*. [Online]. Available: https://nhf.no/for-tillitsvalgte/abc-om-nhf/tall-og-fakta/#:~:text=Antall%5C%20rullestolbrukere%5C%20og%5C%20funksjonshemmede%5C%20i,andre%5C%20har%5C%20den%5C%20som%5C%20avlastning..

[6] W. H. Organization, *Wheelchair services*. [Online]. Available: https://www.who.int/teams/health-product-policy-and-standards/assistive-and-medical-technology/assistive-technology/wheelchair-services.

[7] G. W. Heath and P. H. Fentem, "Physical activity among persons with disabilities–a public health perspective.," *Exercise and sport sciences reviews*, vol. 25, pp. 195–234, 1997.

[8] J. Rimmer, B. Riley, E. Wang, A. Rauworth, and J. Jurkowski, "Physical activity participation among persons with disabilities: Barriers and facilitators," *American journal of preventive medicine*, vol. 26, pp. 419–25, Jul. 2004. DOI: 10.1016/j.amepre.2004.02.002.

[9] M. Howard, "A meta-analysis and systematic literature review of virtual reality rehabilitation programs," *Computers in Human Behavior*, vol. 70, Jan. 2017. DOI: 10.1016/j.chb.2017.01.013.

[10] N. Farič, E. Yorke, L. Varnes, *et al.*, "Younger adolescents' perceptions of physical activity, exergaming, and virtual reality: A qualitative intervention development study," Jun. 2019. DOI: 10.2196/15657.

[11] M. Eckert, I. Gómez-Martinho, J. Meneses, and J.-F. Martínez, "New approaches to exciting exergame-experiences for people with motor function impairments," eng, *Sensors (Basel, Switzerland)*, vol. 17, no. 2, pp. 354–354, 2017, ISSN: 1424-8220.

[12] M. F. Wouda, J.-A. Gaupseth, E. I. Bengtson, T. Johansen, E. A. Brembo, and E. Lundgaard, "Exercise intensity during exergaming in wheelchair-dependent persons with sci," eng, *Spinal cord*, 2023, ISSN: 1362-4393.

[13] S. Yalon-Chamovitz and P. L. (Weiss, "Virtual reality as a leisure activity for young adults with physical and intellectual disabilities," *Research in Developmental Disabilities*, vol. 29, no. 3, pp. 273–287, 2008, ISSN: 0891-4222. DOI: https://doi.org/10.1016/j.ridd.2007.05.004. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0891422207000455.

[14] E. Murray, D. Neumann, R. Moffitt, and P. Thomas, "The effects of the presence of others during a rowing exercise in a virtual reality environment," *Psychology of Sport and Exercise*, vol. 22, Sep. 2015. DOI: 10.1016/j.psychsport.2015.09.007.

[15] J. Enciso, D. Vairya, J. Velasco, *et al.*, "Cloud-based multiplayer exergaming: Developing a platform for social interaction as a motivational tool for exercising in the wheelchair community," eng, in *2020 42nd Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, vol. 2020-, IEEE, 2020, ISBN: 1728119901.

[16] T. Pithon, T. Weiss, S. Richir, and E. Klinger, "Wheelchair simulators: A review," eng, *Technology and disability*, vol. 21, no. 1-2, pp. 1–10, 2009, ISSN: 1055-4181.

[17] J. O'Connor Thomas, S. G. Fitzgerald, R. A. Cooper, T. A. Thorman, and M. L. Boninger, "Kinetic and physiological analysis of the game (wheels) system," English, *Journal of Rehabilitation Research and Development*, vol. 39, no. 6, pp. 627–34, 2002, Copyright - Copyright Superintendent of Documents Nov/Dec 2002; Last updated - 2023-02-21; CODEN - JRRDDB. [Online]. Available: https://www.proquest.com/scholarly-journals/kinetic-physiological-analysis-game-wheels-system/docview/215289689/se-2.

[18] M. A. A. Govindarajan, P. S. Archambault, and Y. L.-E. Haili, “Comparing the usability of a virtual reality manual wheelchair simulator in two display conditions,” *Journal of Rehabilitation and Assistive Technologies Engineering*, vol. 9, p. 20 556 683 211 067 174, 2022, PMID: 35237445. DOI: 10.1177/20556683211067174. eprint: https://doi.org/10.1177/20556683211067174. [Online]. Available: https://doi.org/10.1177/20556683211067174.

[19] T. I. Chowdhury and J. Quarles, “A wheelchair locomotion interface in a vr disability simulation reduces implicit bias,” *IEEE Transactions on Visualization and Computer Graphics*, vol. PP, pp. 1–1, Jul. 2021. DOI: 10.1109/TVCG.2021.3099115.

[20] T. I. Chowdhury, S. M. S. Ferdous, and J. Quarles, “Information recall in a virtual reality disability simulation,” in *Proceedings of the 23rd ACM Symposium on Virtual Reality Software and Technology*, ser. VRST ’17, Gothenburg, Sweden: Association for Computing Machinery, 2017, ISBN: 9781450355483. DOI: 10.1145/3139131.3139143. [Online]. Available: https://doi.org/10.1145/3139131.3139143.

[21] E. Pérez, A. Espacio, S. Salamanca, and P. Merchán, “Wuad (wheelchair user assisted design): A vr-based strategy to make buildings more accessible,” *Applied Sciences*, vol. 12, no. 17, p. 8486, 2022, ISSN: 2076-3417. DOI: 10.3390/app12178486. [Online]. Available: https://browzine.com/articles/533436781.

[22] E. Flatlandsmo, *Wheelchair ergometer game controller*, https://github.com/Embla-Flatlandsmo/wheelchair-ergometer-game-controller, 2023.

[23] *Mcp602 datasheet*, Microchip. [Online]. Available: https://www.microchip.com/en-us/product/MCP602#document-table.

[24] D. Saredakis, A. Szpak, B. Birckhead, H. Keage, A. Rizzo, and T. Loetscher, “Factors associated with virtual reality sickness in head-mounted displays: A systematic review and meta-analysis,” *Frontiers in Human Neuroscience*, vol. 14, Mar. 2020. DOI: 10.3389/fnhum.2020.00096.

[25] *Input system*, Unity Technologies. [Online]. Available: https://docs.unity3d.com/Packages/com.unity.inputsystem@1.6/manual/index.html.

[26] *Input system actions*, Unity Technologies. [Online]. Available: https://docs.unity3d.com/Packages/com.unity.inputsystem@1.6/manual/Actions.html.

[27] *Input system actions*, Unity Technologies. [Online]. Available: https://docs.unity3d.com/Packages/com.unity.inputsystem@1.6/manual/Devices.html.

[28] A. Kemeny, J.-R. Chardonnet, and F. Colombet, *Getting Rid of Cybersickness: In Virtual Reality, Augmented Reality, and Simulators*, eng. Cham: Springer International Publishing AG, 2020, ISBN: 9783030593414.

[29] J. J. LaViola, "A discussion of cybersickness in virtual environments," *SIGCHI Bull.*, vol. 32, no. 1, pp. 47–56, 2000, ISSN: 0736-6906. DOI: 10.1145/333329.333344. [Online]. Available: https://doi.org/10.1145/333329.333344.

[30] A. Mazloumi Gavgani, F. R. Walker, D. M. Hodgson, and E. Nalivaiko, "A comparative study of cybersickness during exposure to virtual reality and "classic" motion sickness: Are they different?" *Journal of Applied Physiology*, vol. 125, no. 6, pp. 1670–1680, 2018, PMID: 30284516. DOI: 10.1152/japplphysiol.00338.2018. eprint: https://doi.org/10.1152/japplphysiol.00338.2018. [Online]. Available: https://doi.org/10.1152/japplphysiol.00338.201.

[31] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *The International Journal of Aviation Psychology*, vol. 3, no. 3, pp. 203–220, 1993. DOI: 10.1207/s15327108ijap0303_3. eprint: https://doi.org/10.1207/s15327108ijap0303_3. [Online]. Available: https://doi.org/10.1207/s15327108ijap0303_3.

[32] H. K. Kim, J. Park, Y. Choi, and M. Choe, "Virtual reality sickness questionnaire (vrsq): Motion sickness measurement index in a virtual reality environment," *Applied Ergonomics*, vol. 69, pp. 66–73, 2018, ISSN: 0003-6870. DOI: https://doi.org/10.1016/j.apergo.2017.12.016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S000368701730282X.

[33] E. Chang, H.-T. Kim, and B. Yoo, "Virtual reality sickness: A review of causes and measurements," *International Journal of Human-Computer Interaction*, vol. 36, pp. 1–25, Jul. 2020. DOI: 10.1080/10447318.2020.1778351.

[34] J. Plouzeau, J.-R. Chardonnet, and F. Merienne, "Using cybersickness indicators to adapt navigation in virtual reality: A pre-study," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, 2018, pp. 661–662. DOI: 10.1109/VR.2018.8446192.

[35] J. T. REASON, "Relations between motion sickness susceptibility, the spiral after-effect and loudness estimation," eng, *The British journal of psychology*, vol. 59, no. 4, pp. 385–393, 1968, ISSN: 0007-1269.

[36] W. B. Stone Iii, *Psychometric evaluation of the simulator sickness questionnaire as a measure of cybersickness*, eng, 2017.

[37] R. Kennedy, J. Drexler, D. Compton, K. Stanney, D. Lanham, and D. Harm, "Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: Similarities and differences," pp. 247–278, Jun. 2003. DOI: 10.1201/9781410608888.ch12.

[38] P. Brown, P. Spronck, and W. Powell, “The simulator sickness questionnaire, and the erroneous zero baseline assumption,” *Frontiers in Virtual Reality*, vol. 3, 2022, ISSN: 2673-4192. DOI: 10.3389/frvir.2022.945800. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frvir.2022.945800.

[39] S. Young, B. Adelstein, and S. Ellis, “Demand characteristics of a questionnaire used to assess motion sickness in a virtual environment,” eng, in *IEEE Virtual Reality Conference (VR 2006)*, IEEE, 2006, pp. 97–102, ISBN: 9781424402243.

[40] P. Kourtesis, J. Linnell, R. Amir, F. Argelaguet, and S. E. MacPherson, “Cybersickness in virtual reality questionnaire (csq-vr): A validation and comparison against ssq and vrsq,” eng, *Virtual Worlds*, vol. 2, no. 1, pp. 16–35, 2023, ISSN: 2813-2084.

[41] H. Critchley and Y. Nagai, “Electrodermal activity (eda),” in *Encyclopedia of Behavioral Medicine*, M. D. Gellman and J. R. Turner, Eds. New York, NY: Springer New York, 2013, pp. 666–669, ISBN: 978-1-4419-1005-9. DOI: 10.1007/978-1-4419-1005-9_13. [Online]. Available: https://doi.org/10.1007/978-1-4419-1005-9_13.

[42] D. Kendzierski and K. J. DeCarlo, “Physical activity enjoyment scale: Two validation studies,” *Journal of sport and exercise psychology*, vol. 13, no. 1, pp. 50–64, 1991, ISSN: 0895-2779.

[43] C. Chen, S. Weyland, J. Fritsch, *et al.*, “A short version of the physical activity enjoyment scale: Development and psychometric properties,” *International Journal of Environmental Research and Public Health*, vol. 18, no. 21, p. 11 035, 2021, ISSN: 1660-4601. DOI: 10.3390/ijerph182111035. [Online]. Available: http://dx.doi.org/10.3390/ijerph182111035.

[44] J. Fritsch, S. Weyland, K. Feil, *et al.*, “A study on the psychometric properties of the short version of the physical activity enjoyment scale in an adult population,” eng, *International journal of environmental research and public health*, vol. 19, no. 22, p. 15 294, 2022, ISSN: 1660-4601.

[45] P. Ben-Nun, *Encyclopedia of survey research methods*, pages 743-743, Thousand Oaks, 2008. DOI: 10.4135/9781412963947. [Online]. Available: https://doi.org/10.4135/9781412963947.

[46] D. C. W. Larry Kenney Jack Wilmore, *Physiology of Sport and Exercise*, 5th ed. Human Kinetics, 2011, ISBN: 0736094091,9780736094092. [Online]. Available: http://gen.lib.rus.ec/book/index.php?md5=2e5e926304101d0d54fc5e1870a91106.

[47] W. Zhu, Y. Li, B. Wang, *et al.*, “Objectively measured physical activity is associated with static balance in young adults,” eng, *International journal of environmental research and public health*, vol. 18, no. 20, p. 10 787, 2021, ISSN: 1660-4601.

[48] P. A. Howarth and S. G. Hodder, “Characteristics of habituation to motion in a virtual environment,” eng, *Displays*, vol. 29, no. 2, pp. 117–123, 2008, ISSN: 0141-9382.

[49] S. Davis, K. Nesbitt, and E. Nalivaiko, "A systematic review of cybersickness," in *Proceedings of the 2014 Conference on Interactive Entertainment*, ser. IE2014, Newcastle, NSW, Australia: Association for Computing Machinery, 2014, pp. 1–9, ISBN: 9781450327909. DOI: 10.1145/2677758.2677780. [Online]. Available: https://doi.org/10.1145/2677758.2677780.

[50] J. Munafo, M. Diedrick, and T. A. Stoffregen, "The virtual reality head-mounted display oculus rift induces motion sickness and is sexist in its effects," eng, *Experimental brain research*, vol. 235, no. 3, pp. 889–901, 2017, ISSN: 0014-4819.

[51] J. F. Golding, "Predicting individual differences in motion sickness susceptibility by questionnaire," eng, *Personality and individual differences*, vol. 41, no. 2, pp. 237–248, 2006, ISSN: 0191-8869.

[52] The pandas development team, *pandas-dev/pandas: Pandas*. [Online]. Available: https://github.com/pandas-dev/pandas.

[53] M. Hill, C. Talbot, and M. Price, "Predicted maximal heart rate for upper body exercise testing," eng, *Clinical physiology and functional imaging*, vol. 36, no. 2, pp. 155–158, 2016, ISSN: 1475-0961.

[54] C. H. Carlsen, D. McGhie, J. K. Baumgart, and Ø. Sandbakk, "Comparison of physiological and biomechanical responses to flat and uphill cross-country sit-skiing in able-bodied athletes," eng, *International journal of sports physiology and performance*, vol. 16, no. 11, pp. 1596–1602, 2021, ISSN: 1555-0273.

[55] "Pearson's correlation coefficient," in *Encyclopedia of Public Health*, W. Kirch, Ed. Dordrecht: Springer Netherlands, 2008, pp. 1090–1091, ISBN: 978-1-4020-5614-7. DOI: 10.1007/978-1-4020-5614-7_2569. [Online]. Available: https://doi.org/10.1007/978-1-4020-5614-7_2569.

[56] P. Virtanen, R. Gommers, T. E. Oliphant, *et al.*, "SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python," *Nature Methods*, vol. 17, pp. 261–272, 2020. DOI: 10.1038/s41592-019-0686-2.

[57] A. C. Mueller, *Wordcloud*, version 1.9.1, Apr. 2023. [Online]. Available: https://github.com/amueller/wordcloud.

[58] L. Rebenitsch and C. Owen, "Review on cybersickness in applications and visual displays," *Virtual Reality*, vol. 20, no. 2, pp. 101–125, 2016. DOI: 10.1007/s10055-016-0285-9.

[59] J. E. Domeyer, N. D. Cassavaugh, and R. W. Backs, "The use of adaptation to reduce simulator sickness in driving assessment and research," eng, *Accident analysis and prevention*, vol. 53, pp. 127–132, 2013, ISSN: 0001-4575.

[60] K.-H. Ladwig, B. Marten-Mittag, B. Formanek, and G. Dammann, "Gender differences of symptom reporting and medical health care utilization in the german population," eng, *European journal of epidemiology*, vol. 16, no. 6, pp. 511–518, 2000, ISSN: 0393-2990.

[61] S. A. Clemes and P. A. Howarth, "The menstrual cycle and susceptibility to virtual simulation sickness," *Journal of Biological Rhythms*, vol. 20, no. 1, pp. 71–82, 2005, PMID: 15654072. DOI: 10.1177/0748730404272567. eprint: https://doi.org/10.1177/0748730404272567. [Online]. Available: https://doi.org/10.1177/0748730404272567.

[62] P. Matchock Robert L., P. Levine Max E., P. Gianaros Peter J., and P. Stern Robert M., "Susceptibility to nausea and motion sickness as a function of the menstrual cycle," eng, *Women's health issues*, vol. 18, no. 4, pp. 328–335, 2008, ISSN: 1049-3867.

[63] S. Smith and S. Du'Mont, "Measuring the effect of gaming experience on virtual environment navigation tasks," eng, in *2009 IEEE Symposium on 3D User Interfaces*, IEEE, 2009, pp. 3–10, ISBN: 1424439655.

[64] J. Jansz and M. Tanis, "Appeal of playing online first person shooter games," *Cyberpsychology & behavior : the impact of the Internet, multimedia and virtual reality on behavior and society*, vol. 10, pp. 133–6, Mar. 2007. DOI: 10.1089/cpb.2006.9981.

[65] T. Hopp and J. Fisher, "Examination of the relationship between gender, performance, and enjoyment of a first-person shooter game," *Simulation & Gaming*, vol. 48, no. 3, pp. 338–362, 2017. DOI: 10.1177/1046878117693397. eprint: https://doi.org/10.1177/1046878117693397. [Online]. Available: https://doi.org/10.1177/1046878117693397.

[66] T. Hartmann, I. Möller, and C. Krause, "Factors underlying male and female use of violent video games," eng, *New media & society*, vol. 17, no. 11, pp. 1777–1794, 2015, ISSN: 1461-4448.

[67] K. Stanney, C. Fidopiastis, and L. Foster, "Virtual reality is sexist: But it does not have to be," *Frontiers in Robotics and AI*, vol. 7, 2020, ISSN: 2296-9144. DOI: 10.3389/frobt.2020.00004. [Online]. Available: https://www.frontiersin.org/articles/10.3389/frobt.2020.00004.

[68] *Does interpupillary distance (IPD) relate to immediate cybersickness?* Jan. 2023. DOI: 10.31234/osf.io/ce4tv.

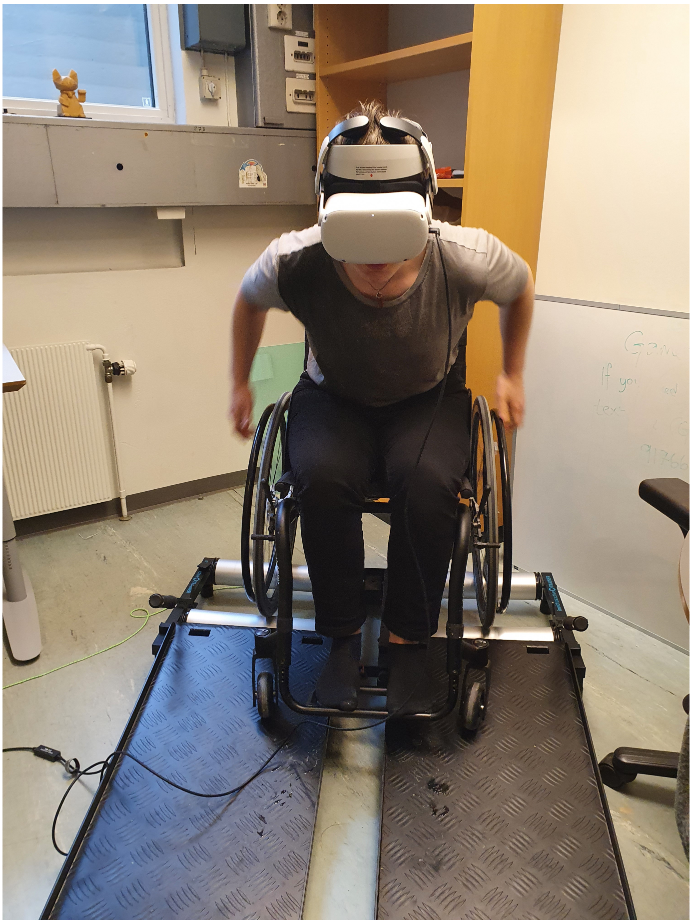
Appendix

A Setup Manual

Wheelchair-enabled Game Controller Setup Manual

Written by Embla Flatlandsmo

May 2023



Contents

1 Introduction

This is a setup manual for turning your Invictus Active Trainer into a device which allows you to play games using your ergometer. It is mainly intended for use with a VR headset, but can also be configured to play other games.

All setup steps pertaining to software are written for Windows 10 (or more recent) operating systems. This system has not been tested for MacOS or Linux.

1.1 Required materials

First and foremost, you need to acquire an Invictus Active Trainer. The modifications that will be done to the trainer are fully reversible, and the trainer will function normally with the modification.

Tools you will need:

- Access to soldering equipment
- Access to a printer
- Tools to screw M3 screws
- Access to and filament for a 3D printer (alternatively you can order this online)

1.1.1 Electroncis

This project requires:

- 1 Adafruit ItsyBitsy nRF52840
- 1 Micro-USB cable, at least 1m.
- USB wall plug (for powering the ItsyBitsy)
- 1 Breadboard
- Breadboard jumper wires
- 4 SparkFun Line Sensor Breakout - QRE1113 (Digital)
- 2 MCP602
- 4 12kΩ resistors
- 12 jumper wires of 15 cm length

Note: All of the items on the purchase list should be possible to buy online through websites such as DigiKey or Farnell.

1.1.2 Screws, nuts and bolts

- 8 pan head screws, about 9mm
- 4 M3 hex socket bolts, about 15mm
- 2 M3 countersunk head bolts, about 13mm
- 4 M3 hex nuts
- 2 M3 flat washers

2 Setting up the Adafruit ItsyBitsy nRF52840 (electronics)

First, you must solder on the male connectors that are included in the package of the Adafruit ItsyBitsy nRF52840. The SparkFun line sensors must be soldered in the same way. After this, place it on one end of the breadboard, shown in fig. 1.

2.1 Wiring

The wiring required for the setup to work are described in fig. 1 and table 1. Use the breadboard to wire the connections as shown in fig. 1. The schematics of the circuit are given in section 2.1.1.

Pin	**Name**
SCK	Right side, back sensor
MO	Right side, front sensor
D13	Left side, back sensor
D12	Left side, front sensor

Table 1: ItsyBitsy and sensor wirings

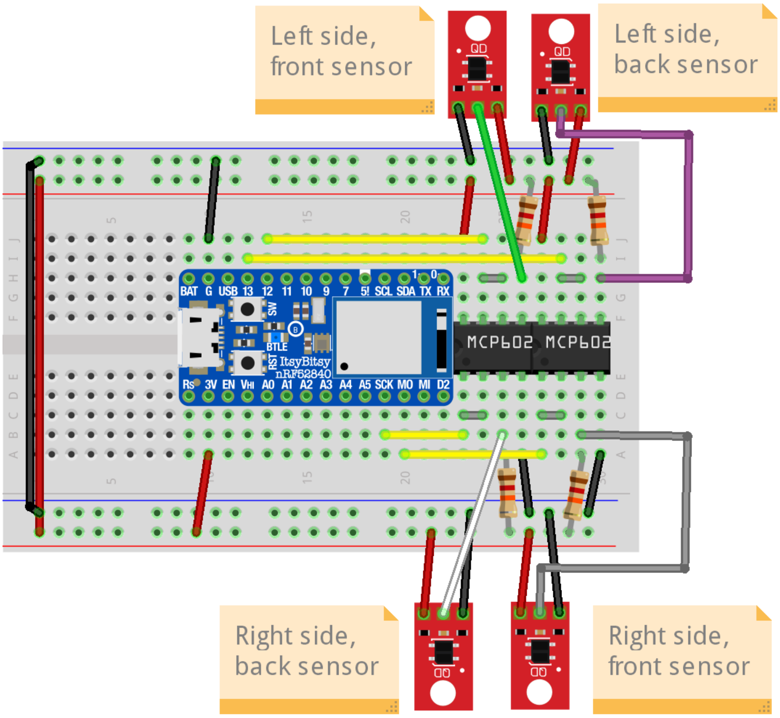


Figure 1: Suggestion for physical wiring of encoders

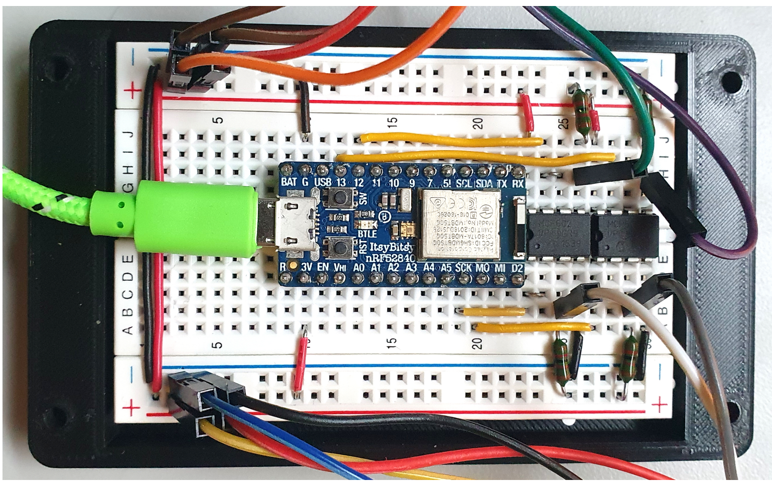


Figure 2: Picture of how the author wired the electronics

2.1.1 Schematics

If you followed the wiring as shown in fig. 1 you may disregard figs. 3 and 4. These are the schematics for those who are particularly interested in the inner workings of the circuit.

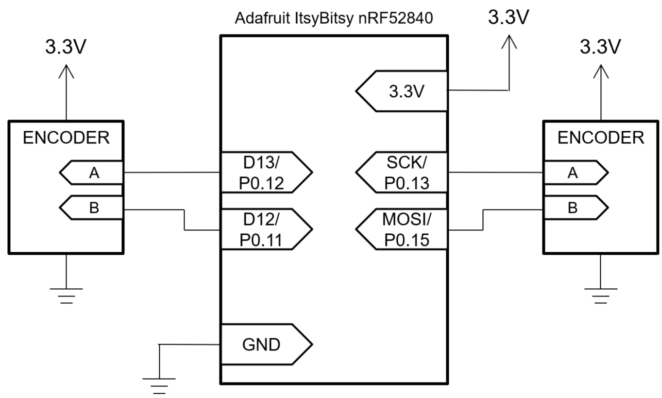


Figure 3: Schematic for the Adafruit ItsyBitsy nRF52840

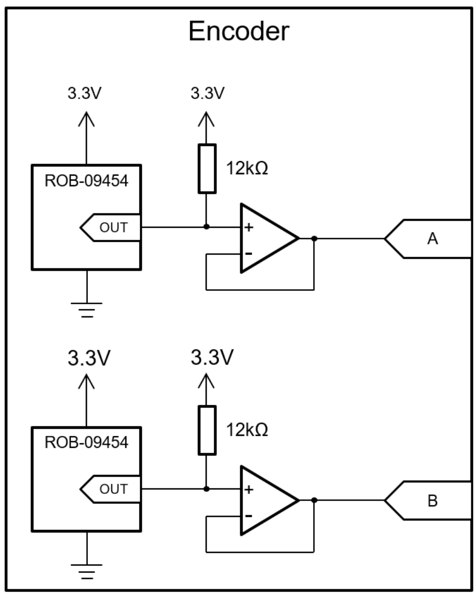
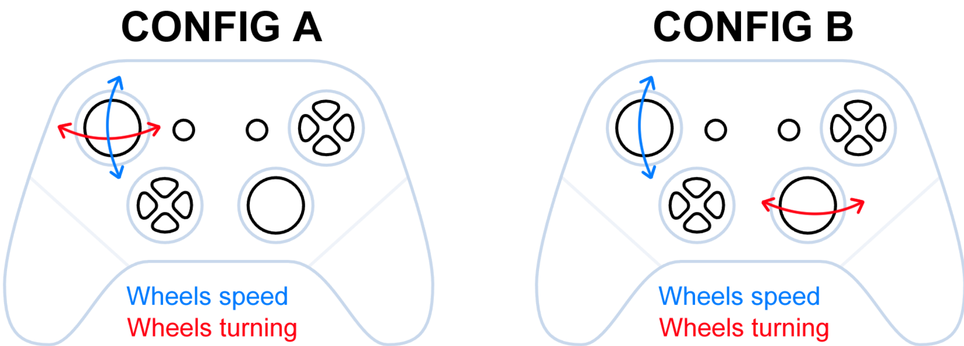


Figure 4: Schematic for the encoder

2.2 Software setup

Different games have different types of input. Because of this, two different configurations have been provided. These are shown in fig. 5.



(a) Config A

(b) Config B

Figure 5: Gamepad configurations

2.2.1 First time setup

The ItsyBitsy comes with the Adafruit UF2 bootloader. This bootloader must be updated as described in the Adafruit nRF52840 guide (note that this guide is for the nRF52840 Feather, but the same applies ItsyBitsy nRF52840). I have only gotten it to work following the command line instructions part of the tutorial.

2.2.2 Uploading the firmware

To upload the firmware that turns the ItsyBitsy into the game controller unit, do the following:

1. Double tap the `RST` button on the ItsyBitsy (shown in Figure 6)
2. A storage device named `ITSYBOOT` should have appeared. To see this, press Windows+E and go to "This PC".
3. Drag the `.uf2` file for the config you want (see Figure 5) into `ITSYBOOT`. The device should rapidly flash red before disappearing as a storage device.

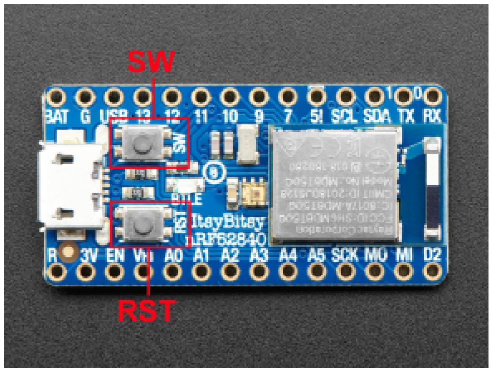


Figure 6: Location of buttons on the Adafruit ItsyBitsy nRF52840

3 Hardware setup

This section describes the mechanical steps needed to set up the device.

3.1 Encoder mounting

This section outlines how to set up the encoder and electronics mounted shown in fig. 7.

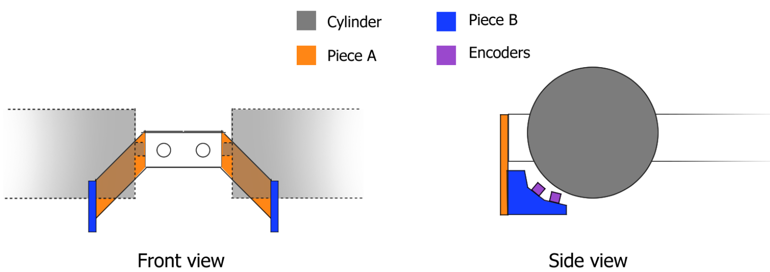


Figure 7: Encoder mounting design

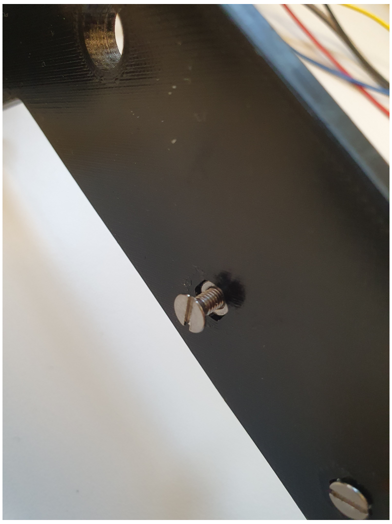
3.1.1 3D printing

Start out by 3D printing the attached `.stl` files.

3.1.2 Electronics box mounting

The box will be attached to the encoder mounting. This is done by using the hex nuts, washers and countersunk screws.. To make it possible to attach the electronics box, you must:

1. For piece A, insert one hex nut into each slot
2. Insert the countersunk screws so that the head is on the same side as the hex nuts (fig. 8a)
3. On the opposite side, place one washer and one hex nut for each screw (fig. 8b)



(a) Piece A, front

(b) Piece A, back

Figure 8: Piece A nut, washer and bolt placement

3.1.3 Line Sensor mounting

Screw the line sensors onto the two separate B pieces, using the pan head screws shown in fig. 9

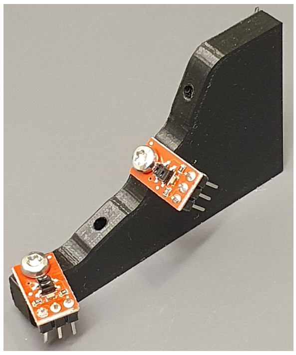


Figure 9: Piece B with line sensors mounted

3.1.4 Combining piece A and B

Use the remaining pan head screws to fasten Piece A and the B pieces together as shown in fig. 10. You may move the B pieces up and down slightly. The encoders must be **as close to the roller as possible** for them to register the paper.

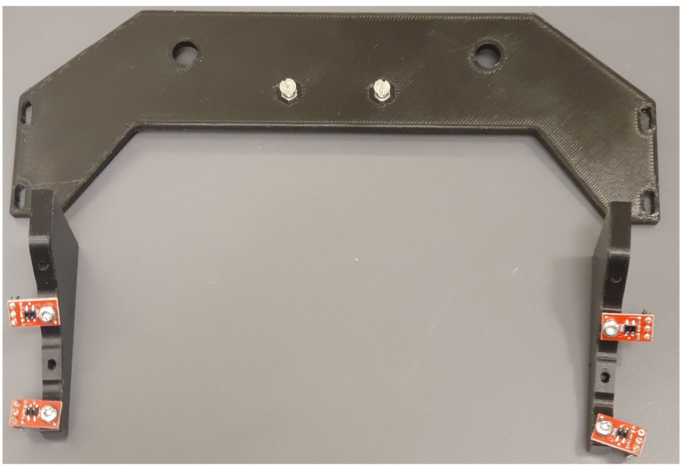


Figure 10: How piece A and B should be combined

3.2 Encoder bands

Print the attached .pdf file of the encoder bands, then attach them around the inner side of each rear roller on the ergometer. Use glue, not tape.

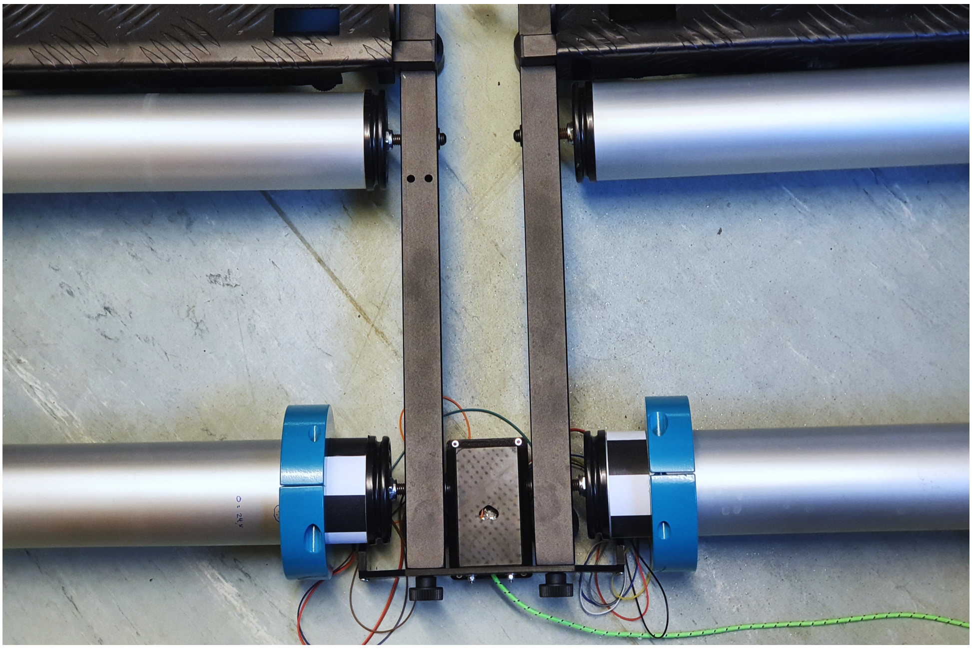


Figure 11: Attachment of encoder bands around the rollers

3.3 Electronics box

1. Insert four hex nuts at the bottom of the box
2. Place the electronics inside the box
3. Close the lid using the 4 M3 hex socket bolts. Ensure that the wires may pass through the appropriate holes.

3.4 The final mounting

1. Remove the two big screws and metal plate that keep the beams of the trainer aligned. They are at the back of the invictus active trainer.

2. Slide the electronics box between the two beams of the trainer

3. Place the line sensor mounting piece over the holes at the back of the beams, then use the original screws to attach the piece.

The box is attached to piece A and slid between the two beams of the Invictus Active trainer as

4 Troubleshooting

4.1 Light signals and their meaning

Table 2 shows the light color and blinks emitted from the ItsyBitsy and what they mean.

Color	Number of times	Duration	Meaning
Green	1	Long	The device successfully booted
Blue	1-10	Long	The device is advertising itself as "Wheelchair Ergometer". It should be found when you scan for it.
Orange	2	Medium	The device is connected but the connection is not secure.
Green	2	Medium	The device is connected and the connection is secure
Red	5	Short	The device failed to connect to its peer
Red	2	Short	The device was disconnected from its peer

Table 2: Light meaning for ItsyBitsy

4.2 The device connects to my PC but it does not create any output

To check that everything is alright with your device, try to upload the firmware `SIMULATED_INPUT`. If it seems to work when using this file, the problem(s) might be:

- Incorrect wiring: Check that the wiring is correct
- Encoders are too far from the pipes: They need to be really close.
- Bad paper or ink

4.3 Known problems

4.3.1 The device disconnects frequently

It has been discovered that the Bluetooth connection might get knocked out if there are a lot of phones around the device. This problem seems to be alleviated upon setting phones in flight mode and disabling their Bluetooth feature.

If the device is still disconnected, try restarting the device by disconnecting and connecting the power cable of the device.

4.3.2 The device will not pair anew after being unpaired

There is currently a problem in the device where it is unable to forget another device which has requested to unpair. To fix this, you need to clear all pairings from the device manually. Do this by:

1. Unpair the device on your computer/phone/VR headset
2. Press `RST` once on the Adafruit ItsyBitsy nRF52840
3. Within 5 seconds of pressing `RST`, double tap the `SW` button.
4. The device should now act as if it was new, having forgotten all of the paired devices.

B SSQ translation

English	Norwegian
General discomfort	Generelt ubehag
Fatigue	Tretthet
Headache	Hodepine
Eyestrain	Vondt i øynene
Difficulty focusing	Fokuseringsvansker
Increased salivation	Økt spyttproduksjon
Sweating	Svette
Nausea	Kvalme
Difficulty concentrating	Konsentrasjonsvansker
Fullness of head	Tungt eller trangt hode
Blurred vision	Uklart syn
Dizzy (eyes open)	Svimmelhet (åpne øyne)
Dizzy (eyes closed)	Svimmelhet (lukkede øyne)
Vertigo	Verden snurrer
Stomach awareness	Magebevissthet
Burping	Raping

Table 7.1: English to Norwegian translation of SSQ items

C PACES-S translation

English	Norwegian
I enjoyed the activity	Jeg nøt aktiviteten
I found the activity pleasurable	Jeg synes aktiviteten var lystbetont
The activity was very pleasant	Aktiviteten var veldig hyggelig
The activity felt good	Aktiviteten føltes bra

Table 7.2: English to Norwegian translation of PACES-S items

D Sikt Meldeskjema

Sikt

Meldeskjema / User Experience for a Wheelchair Exergame Device / Eksport

Meldeskjema

Referansenummer
935703

Hvilke personopplysninger skal du behandle?

- Navn (også ved signatur/samtykke)
- Fødselsdato
- Helseopplysninger

Prosjektinformasjon

Prosjekttittel

User Experience for a Wheelchair Exergame Device

Prosjektbeskrivelse

We are developing a wheelchair exercise game device at NTNU and wish to evaluate various parts of this device through user testing. Most importantly, we wish to evaluate if and to which degree the participants become "VR-sick" from using the device. This will be done through a standardized questionnaire, namely the Virtual Reality Sickness Questionnaire (VRSQ).

Additionally, we will measure heart rate to see if there is a pattern between this and how VR-sick a user feels. We will also ask questions about the user's overall experience with VR, if they are a wheelchair user and what their thoughts (if any) on the device are.

Dersom personopplysningene skal behandles til andre formål enn behandlingen for dette prosjektet, beskriv hvilke

N/A

Begrunn hvorfor det er nødvendig å behandle personopplysningene

The participants age might influence how/if they become sick from VR. Past experience with VR is also an influence on how VR sick a person gets.

The VR Sickness Questionnaire (VRSQ) will be the main way of measuring how VR sick they are. Elevated heart rate is linked to an increased rate of VR sickness so we want to measure that too.

Wheelchair users will be asked to share their thoughts on the device so that we might develop something that wheelchair users will actually have had a say in.

Ekstern finansiering
Ikke utfyllt
Type prosjekt
Studentprosjekt, masterstudium

Kontaktinformasjon, student
Embla Flatlandsmo, emblaf@stud.ntnu.no, tlf: 91766794

Behandlingsansvar

Behandlingsansvarlig institusjon
Norges teknisk-naturvitenskapelige universitet / Fakultet for medisin og helsevitenskap (MH) / Institutt for nevromedisin og bevegelsesvitenskap

Prosjektansvarlig (vitenskapelig ansatt/veileder eller stipendiat)
Julia Kathrin Baumgart, julia.k.baumgart@ntnu.no, tlf: 48436206

Skal behandlingsansvaret deles med andre institusjoner (felles behandlingsansvarlige)?
Nei

Utvalg 1

Beskriv utvalget

First round: Early testers

Beskriv hvordan rekruttering eller trekking av utvalget skjer

Recruitment will take place through personal and work-related networks as well as social media.

Alder
18 - 65

Personopplysninger for utvalg 1

- Navn (også ved signatur/samtykke)
- Fødselsdato
- Helseopplysninger

Hvordan samler du inn data fra utvalg 1?

Elektronisk spørreskjema

Vedlegg

VR_Questionnaire.docx

Grunnlag for å behandle alminnelige kategorier av personopplysninger
Samtykke (Personvernforordningen art. 6 nr. 1 bokstav a)

Grunnlag for å behandle særlige kategorier av personopplysninger
Uttrykkelig samtykke (Personvernforordningen art. 9 nr. 2 bokstav a)

Redegjør for valget av behandlingsgrunnlag

Informasjon for utvalg 1

Informerer du utvalget om behandlingen av personopplysningene?
Ja

Hvordan?
Skriftlig informasjon (papir eller elektronisk)

Informasjonsskriv

DigiWR informed consent 23.02.docx

Utvalg 2

Beskriv utvalget

Second round: Wheelchair users

Alder
18 - 65

Personopplysninger for utvalg 2

- Navn (også ved signatur/samtykke)
- Fødselsdato
- Helseopplysninger

Hvordan samler du inn data fra utvalg 2?

Elektronisk spørreskjema

Vedlegg

VR_Questionnaire.docx

Grunnlag for å behandle alminnelige kategorier av personopplysninger
Samtykke (Personvernforordningen art. 6 nr. 1 bokstav a)

Grunnlag for å behandle særlige kategorier av personopplysninger
Uttrykkelig samtykke (Personvernforordningen art. 9 nr. 2 bokstav a)

Redegjør for valget av behandlingsgrunnlag

Informasjon for utvalg 2

Informerer du utvalget om behandlingen av personopplysningene?
Ja

Hvordan?
Skriftlig informasjon (papir eller elektronisk)

Informasjonsskriv

DigiWR informed consent 23.02.docx

Tredjepersoner

Skal du behandle personopplysninger om tredjepersoner?
Nei

Dokumentasjon

Hvordan dokumenteres samtykkene?

- Elektronisk (e-post, e-skjema, digital signatur)

Hvordan kan samtykket trekkes tilbake?

My contact details have been provided and participants can contact me to take back their consent. All information of the participants in question will immediately be deleted.

Hvordan kan de registrerte få innsyn, rettet eller slettet personopplysninger om seg selv?

My contact details are provided in the consent form and participants can contact me to get insight into, correct or delete their data.

Totalt antall registrerte i prosjektet
1-99

Tillatelser

Skal du innhente følgende godkjenninger eller tillatelser for prosjektet?
Ikke utfyllt

Behandling

Hvor behandles personopplysningene?

- Maskinvare tilhørende behandlingsansvarlig institusjon
- Mobile enheter tilhørende behandlingsansvarlig institusjon
- Fysisk isolert maskinvare tilhørende behandlingsansvarlig institusjon
- Ekstern tjeneste eller nettverk (databehandler)

Hvem behandler/har tilgang til personopplysningene?

- Prosjektansvarlig
- Student (studentprosjekt)
- Interne medarbeidere
- Databehandler

Hvilken databehandler har tilgang til personopplysningene?

Nettskjema.

Tilgjengeliggjøres personopplysningene utenfor EU/EØS til en tredjestat eller internasjonal organisasjon?
Nei

Sikkerhet

Oppbevares personopplysningene atskilt fra øvrige data (koblingsnøkkel)?
Ja

Hvilke tekniske og fysiske tiltak sikrer personopplysningene?

- Personopplysningene anonymiseres fortløpende
- Adgangsbegrensning

Varighet

Prosjektperiode
01.03.2023 - 15.07.2023

Hva skjer med dataene ved prosjektslutt?
Data anonymiseres (sletter/omskriver personopplysningene)

Hvilke anonymiseringstiltak vil bli foretatt?

- Personidentifiserbare opplysninger fjernes, omskrives eller grovkategoriseres
- Koblingsnøkkelen slettes

Vil de registrerte kunne identifiseres (direkte eller indirekte) i oppgave/avhandling/øvrige publikasjoner fra prosjektet?
Nei

Tilleggsopplysninger

E Consent Form

NTNU
Kunnskap for en bedre verden

Would you like to participate in the research project «The Digital Wheelchair in VR» - Exercise and gaming in VR for wheelchair users?

The goal of the research project

In Norway there are approximately 50 000 people, and on a world basis about 75 million people that use a wheelchair for everyday activities. Everyday life is not just a greater challenge for wheelchair users, but they are also less likely to engage in an active lifestyle and often have a worse physical and mental health when compared to the general population. In an effort to promote an active lifestyle and improve the general health of wheelchair users, we wish to explore possibilities of making exercise more fun and accessible. The main goal of this project is therefore to explore a potential technology that makes regular exercise an achievable goal.

What is expected of participants?

Participants will test a wheelchair ergometer which is connected to a VR headset. The participant will be asked to navigate around an obstacle course in a virtual environment as many times as they can in 15 minutes. After this, the participant will answer a questionnaire where they assess the degree of various symptoms of "cyber sickness" before they are asked to give feedback about the holistic experience of the device. It is important to note that the goal of the study is not to make participants cyber sick. Rather, it is about assessing whether users experience experience symptoms of cyber sickness when using the device. The following variables will be registered/measured: Age, gender, type and degree of physical disability, past experience with VR, self-assessment of symptoms of cyber sickness, thoughts about areas of improvements of the experience, as well as heart rhythm over the span of the play time.

Why participate?

The project results will be used for research and the further development of a fun and accessible training option for wheelchair users. The project is in its early phase and we wish to figure out whether this device can help motivate wheelchair users to exercise more. This will promote a more active and healthy lifestyle with the goal of helping wheelchair users improve both their health and quality of life. Your participation will contribute to developing more exercise options for wheelchair users.

Who may participate?

Healthy individuals between 18 and 65 years, regardless of gender.

Possible benefits and drawbacks

Direct benefits for you as a participant is the possibility to try new technology and give direct feedback that can affect the final device. The drawback is that you have to spend 30 minutes completing the test.

Voluntary participation

Participation in the project is voluntary. You do not need to give a reason if you do not wish to participate or if you choose to withdraw from the project at any point in time.

What happens to the collected data?

The data we collect on you will only be used as described in the section "The goal of the research project" and the plan is to use it until 2030. Your data will be anonymized after the end of the project and is stored/archived in an indeterminate amount of time for use in potential follow-up studies or further research. Eventual extensions in use and storage time will only happen if you consent to this.

Your name and contact information will be replaced with a code that is stored separate from other data and is locked in a locker in the office of Damiano Varagnolo. All data will be deidentified before storage. Access to the stored deidentified information will be controlled by the project leader and is based on a data handling plan from Data Stewardship Wizard. Deidentified raw data will be accessible as "open access" through a verified database. The lead scientist and the research group will have access to the data. You have the rights to: See what data is stored about you, have your data corrected/adjusted, have your data removed, receive a copy of your data (dataportability) and send a complaint to the Norwegian Data Protection Authority or Datatilsynet about the treatment of your data.

Results

The results of this project will be published through multiple international publications and presentations on national and international conferences. The deidentified data will also be made accessible (open access) in a verified online database. It will not be possible to identify any of the participants. For questions regarding the results, contact the lead researched via e-mail (julia.k.baumgart@ntnu.no)

Approvals

SIKT has assessed and approved this project (ID 935703). Department of Neuromedicine and Movement Science (INB) and project leader Julia Kathrin Baumgart is responsible for the data protection in the project. We treat the data based on your consent.

Contact information

If you have questions about the study, or wish to exercise your privacy rights, please contact:

- Julia Kathrin Baumgart ved Institutt for Nevromedisin og Bevegelsesvitenskap, NTNU, via e-mail (julia.k.baumgart@ntnu.no).
- Our data protection services: Thomas Helgesen, director of data protection, NTNU, via e-mail (thomas.helgesen@ntnu.no).
- Data protection services at SIKT, via e-mail (personverntjenester@sikt.no) or by phone: 73 98 40 40.

Samtykkeerklæring

I have read the information given. I consent to participate in this project and that my personal data is used as it has been described

----

Place and Date　　　　　　　　　　Participant’s signature

Participant’s name in print letters

F Post-test Questionnaire

Post-test Questionnaire

Note: *The questionnaire was originally issued using Nettskjema. The questions are given in Norwegian first, then English in the parentheses. Users were encouraged to use the english definitions for the symptoms assessment.*

Symptomer knyttet til VR-gaming (Symptoms related to VR gaming)

Vurder i hvilken grad du opplever følgende symptomer (Rate your experience of the following symptoms)

	Ikke i det hele tatt *(Not at all)*	**Litt *(A little)***	**Moderat *(Moderately)***	**Veldig *(Very)***
Generelt ubehag *(General Discomfort)*				
Tretthet *(Fatigue)*				
Hodepine *(Headache)*				
Vondt i øynene *(Eyestrain)*				
Fokuseringsvansker *(Difficulty focusing)*				
Økt spyttproduksjon *(Increased salivation)*				
Svette *(Sweating)*				
Kvalme *(Nausea)*				
Konsentrasjonsvansker *(Difficulty concentrating)*				
Tungt eller trangt hode *(Fullness of head)*				
Uklart syn *(Blurred Vision)*				
Svimmelhet (Åpne øyne) *(Dizzy (eyes open))*				
Svimmelhet (Lukkede øyne) *(Dizzy (eyes closed))*				
Verden snurrer *(Vertigo)*				
Magebevissthet *(Stomach Awareness)*				
Raping *(Burping)*				

Nytelse av spillet/konseptet (Enjoyment of the game/concept)

Tenk på aktiviteten du akkurat gjorde og ranger følgende påstander:

	Sterkt Uenig *(Strongly Disagree)*	Uenig *(Disagree)*	Nøytral *(Neutral)*	Enig *(Agree)*	Veldig Enig *(Strongly Agree)*
Jeg nøt aktiviteten *(I enjoyed the activity)*					
Jeg synes aktiviteten var lystbetont *(I found the activity pleasurable)*					
Aktiviteten var veldig hyggelig *(The activity was very pleasant)*					
Aktiviteten føltes bra *(The activity felt good)*					

Ville du helst spilt et slikt treningsspill med eller uten VR-briller? (Would you prefer to play an exercise game like this with or without a VR headset?)

- Jeg foretrekker å spille det med VR-briller (I would prefer to play it with a VR headset)
- Jeg ville foretrukket å spille det på en vanlig skjerm (I would prefer to play it on a normal screen)
- Vet ikke (Don't know)

Fødselsdato (Date of Birth)

Kjønn (Gender)

- Mann (Male)
- Kvinne (Female)
- Annet (Other)

Høyde i cm (Height in centimeters)

Blir du lett sjøsyk/kjøresyk/reisesyk? (Are you prone to experiencing motion sickness?)

- Ja (Yes)
- Nei (No)

I de siste 6 månedene, hvor ofte har du spilt VR-spill? (In the past 6 months, how often have you played VR games?)

- Regelmessig, 4-7 dager i uka (Regularly, 4-7 days a week)
- Regelmessig, 1-3 dager i uka (Regularly, 1-3 days a week)
- Regelmessig, 1-3 dager i måneden (Regularly, 1-3 days a month)
- Uregelmessig, et par ganger i året (Irregularly, a couple of times a year)
- Aldri (Never)

Hvor ofte gjør du kondisjonstrening? (How often do you train your cardiovascular activity?)

- Mer enn 3 dager i uka (More than 3 times per week)
- 2-3 ganger i uka (2-3 times per week)
- 1-2 ganger i uka (1-2 times per week)
- 1-3 ganger i måneden (1-3 times per month)
- Sjelden (Rarely)
- Aldri (Never)

Er du en rullestolbruker? (Are you a wheelchair user?)

- Ja (Yes)
- Nei (No)

Øvrige tilbakemeldinger (General feedback)

Har du noen tilbakemeldinger eller idéer til måten undersøkelsen ble gjort på, eller kanskje til videreutviklingen av dette apparatet? Vennligst skriv det inn, dine tanker er viktige! (Do you have any feedback or ideas for the further development of this device? Please let us know, your thoughts are important!)

G Procedure for Exergame Platform Test Run

Materials to run the tests:

- VR Headset and the 2 controllers
- A PC that meets the requirements to use Meta Quest Link
- Meta Quest Link Cable
- The exergame platform, complete with electronics
- Micro-USB to power the exergame platform
- Empatica 4 wristband
- Polar smart watch
- Polar H10 pulse belt

Before starting out, the VR headset needs to be in the Quest Link app. This is done by:

1. Connecting the VR headset to the PC via USB
2. Opening the ”Oculus” app on the PC
3. Enabling Oculus Link on the headset by going to Settings ¿ System ¿ Quest Link ¿ ”Launch Quest Link” then pressing ”Launch” once it finds ”Rift”

The PC is running the game with the Unity game engine. This is done by opening the Unity Hub, then opening the ”VR-wheelchair-game” project.

Step-by-step for each test run

1. The participant fills out the consent form
2. Clean the VR headset, pulse belt and Empatica 4
3. Set the logger file configurations in the Unity editor:
   - In the ”Hierarchy” window, press ”Timer and Logistics”
   - In the ”Inspector” window, type the participant’s date of birth into the ”Output File Name” field under ”Logger (Script)”. **Also ensure that ”Save Data” is ticked** in the ”Logger (Script)” section.
4. Apply some water to the pulse belt. Ask the participant to put on the pulse belt and the empatica 4. They do not need to wear the Polar watch.
5. Explain the game (see below)
6. If the participant is wearing a lot of clothing, tell them that playing the game will likely make them pretty hot and it’s recommended to wear a t-shirt.

7. Start the Empatica 4 data collection by pressing the button on the Empatica 4 and waiting for 40 seconds until the LED turns red. This means the Empatica enters offline data collection.

8. Start the Polar HR data collection by starting the ”VR trial” activity in the ”Favorites” section on the Polar watch.

9. Have the user put on the VR headset. They may make adjustments to the eye screens and the headset strap to make it fit as good as possible.

10. In the Unity Editor, press the ”Play” button. The player should now enter the game (and the timer has started).

11. When in the game, center the player onto the wheelchair by doing the following:

    - On the right-hand VR controller, press the button
    - In the bottom of the ”Unity” window, select ”Reset View” by pointing at it and pressing ”A”
    - Sit back in the wheelchair, look straight ahead and press

12. The participant plays until the game freezes (10 or 15 minutes).

13. Immediately after the time is up, turn off the Empatica and end the polar training session.

14. The participant immediately fills out the questionnaire

15. While the participant fills out the questionnaire, download the Polar, Empatica and game data into the system described in ”Data Orgnaization” below.

About the game

- Preferably you will play until the game stops, but you are allowed to end it early if you feel sick or unwell. Feeling tired in your arms from moving or feeling bored of the game is not a valid reason to end early.

- The red line signifies the start of the lap.

- The blue lines are checkpoints.

- You need to cross all the checkpoints in order to complete a lap.

- The time starts the moment you're in the game. We have a record over the best lap times

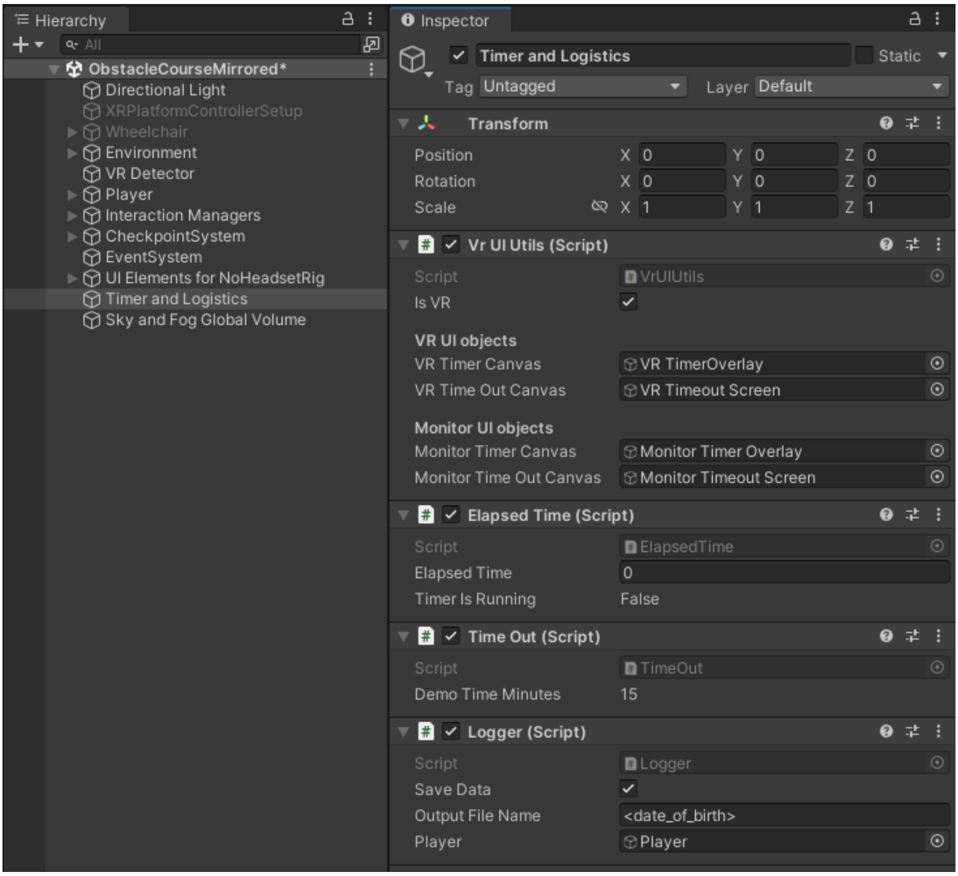


Figure 7.1: In-game settings for a test run

Data Organization

The Polar, Empatica and game data is stored in the data/sensor_data folder. The data for each participant is stored in the folder corresponding to the date of birth of the participant. The polar data is in a file that starts with VR_Polar, the game data starts with game_data and the empatica data is in the empatica folder.

Structure of the game data

- The first row contains speed and turning multipliers for the game setup. This describes how sensitive the device was to forwards and turning signals.
- The second row contains headers for the real-time data collection. This is cumulative movement, cumulative rotation, sample time stamp and lap number. The sampling rate is 1Hz.
- The rest of the rows are data
- The final row stores the best lap time for the course and the total time (in seconds) the participant played for.

Structure of the Polar data

The session data output by the polar pulse belt is given in one .csv file. The contents of the rows are:

- Row 1-2 contains headers and data for a summary of the training session.
- Row 3 and onwards contains real-time data such as heart rate and elapsed training time, sampled at 1Hz.
- From row 1-2 only ”start time” and ”date” is used, and from row 3 and onwards, ”time” and ”HR” is used.

Structure of the Empatica 4 Data

For each session, the Empatica 4 records 7 different types of data. This data is stored in separate .csv files, and the name and description of each file is shown in table 7.3.

File	Unit	Description
TEMP	$^{\circ}$C	Temperature
EDA	μS	Electrodermal Activity
BVP	N/A	Photoplethysmograph
ACC	1/64g	Accelerometer x,y,z
IBI	s	Time between individuals heart beats, extracted from BVP signal
HR	beats per minute	Average heart rate, extracted from BVP signal
tags	N/A	Event mark times

Table 7.3: Data from Empatica 4

The rows of the files contain the following:

- The first row is the inital time of the session expressed as UNIX timestamp in UTC.
- The second row is the rample rate expressed in Hz
- The rest of the rows contain real-time data.

H VR Recruitment poster

I Pearson’s correlation coefficient and p-values for final round variables

	Gender	MS prone	VR habits	Cardio habits	Height	Age	SSQ: Total	PACES-S	Play Time (%)	%HR_{peak}	Avg EDA	Avg Movt Speed	Avg Turn Speed
Gender	1.000	0.613	0.508	0.258	-0.734	-0.021	0.413	-0.421	-0.371	0.037	0.045	-0.344	-0.511
MS prone	0.613	1.000	0.340	0.098	-0.522	0.018	0.555	-0.526	-0.384	-0.146	0.050	-0.488	-0.605
VR habits	0.508	0.340	1.000	0.082	-0.559	-0.368	-0.051	0.050	0.153	0.264	-0.238	0.138	-0.107
Cardio habits	0.258	0.098	0.082	1.000	-0.090	-0.246	0.075	0.016	0.195	-0.423	-0.040	-0.039	0.158
Height	-0.734	-0.522	-0.559	-0.090	1.000	0.235	-0.238	0.264	0.215	-0.181	0.171	0.263	0.309
Age	-0.021	0.018	-0.368	-0.246	0.235	1.000	0.048	-0.015	-0.534	0.191	0.327	-0.057	-0.116
SSQ: Total	0.413	0.555	-0.051	0.075	-0.238	0.048	1.000	-0.817	-0.480	-0.430	-0.003	-0.566	-0.514
PACES-S	-0.421	-0.526	0.050	0.016	0.264	-0.015	-0.817	1.000	0.459	0.442	0.045	0.750	0.690
Play Time (%)	-0.371	-0.384	0.153	0.195	0.215	-0.534	-0.480	0.459	1.000	-0.069	-0.224	0.403	0.377
%HR_{peak}	0.037	-0.146	0.264	-0.423	-0.181	0.191	-0.430	0.442	-0.069	1.000	0.235	0.614	0.245
Avg EDA	0.045	0.050	-0.238	-0.040	0.171	0.327	-0.003	0.045	-0.224	0.235	1.000	-0.010	-0.065
Avg Movt Speed	-0.344	-0.488	0.138	-0.039	0.263	-0.057	-0.566	0.750	0.403	0.614	-0.010	1.000	0.656
Avg Turn Speed	-0.511	-0.605	-0.107	0.158	0.309	-0.116	-0.514	0.690	0.377	0.245	-0.065	0.656	1.000

Figure 7.2: Pearson’s correlation coefficients

	Gender	MS prone	VR habits	Cardio habits	Height	Age	SSQ: Total	PACES-S	Play Time (%)	%HR_{peak}	Avg EDA	Avg Movt Speed	Avg Turn Speed
Gender	0.00000	0.00088	0.00805	0.20336	0.00002	0.91960	0.03592	0.03240	0.06235	0.85695	0.82756	0.08499	0.00760
MS prone	0.00088	0.00000	0.08905	0.63530	0.00623	0.92961	0.00325	0.00577	0.05255	0.47772	0.80717	0.01138	0.00105
VR habits	0.00805	0.08905	0.00000	0.69108	0.00302	0.06446	0.80272	0.80823	0.45535	0.19210	0.24236	0.50161	0.60227
Cardio habits	0.20336	0.63530	0.69108	0.00000	0.66355	0.22565	0.71639	0.93682	0.33917	0.03147	0.84651	0.85151	0.44026
Height	0.00002	0.00623	0.00302	0.66355	0.00000	0.24859	0.24112	0.19297	0.29241	0.37670	0.40371	0.19461	0.12392
Age	0.91960	0.92961	0.06446	0.22565	0.24859	0.00000	0.81768	0.94236	0.00493	0.35043	0.10271	0.78154	0.57138
SSQ: Total	0.03592	0.00325	0.80272	0.71639	0.24112	0.81768	0.00000	0.00000	0.01300	0.02818	0.98773	0.00260	0.00727
PACES-S	0.03240	0.00577	0.80823	0.93682	0.19297	0.94236	0.00000	0.00000	0.01826	0.02373	0.82802	0.00001	0.00010
Play Time (%)	0.06235	0.05255	0.45535	0.33917	0.29241	0.00493	0.01300	0.01826	0.00000	0.73791	0.27137	0.04123	0.05766
%HR_{peak}	0.85695	0.47772	0.19210	0.03147	0.37670	0.35043	0.02818	0.02373	0.73791	0.00000	0.24716	0.00085	0.22766
Avg EDA	0.82756	0.80717	0.24236	0.84651	0.40371	0.10271	0.98773	0.82802	0.27137	0.24716	0.00000	0.95962	0.75068
Avg Movt Speed	0.08499	0.01138	0.50161	0.85151	0.19461	0.78154	0.00260	0.00001	0.04123	0.00085	0.95962	0.00000	0.00028
Avg Turn Speed	0.00760	0.00105	0.60227	0.44026	0.12392	0.57138	0.00727	0.00010	0.05766	0.22766	0.75068	0.00028	0.00000

Figure 7.3: P-values for correlation coefficients

NTNU

Norwegian University of
Science and Technology