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Analysis of Dual-Sided Cycling Power in a Virtual Reality Game

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Michaela Niedermayer

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Kurzfassung

Virtuelle Realität ist ein wachsender Bereich, indem sich durch immer besser werdende Hardware äußerst realitätsnahe Anwendungen realisieren lassen. Dabei bietet die virtuelle 3D Umgebung viele Möglichkeiten für visuelles Feedback.

In dieser Diplomarbeit wollen wir visuelles Feedback in einer Anwendung einsetzen, um einen Benutzer zu zeigen, ob seine rechte und linke Beinkraft gleichverteilt ist. Des Weiteren soll die Anwendung dazu dienen eine mögliche Asymmetrie in der Beinkraftverteilung durch häufigere Nutzung zu verbessern. Die Anwendung ist für die Verwendung im Physiotherapie-Bereich entwickelt worden, speziell für Personen mit Bein, Knie oder Fuß Verletzungen und nach Operationen in einen dieser Bereiche, da betroffene Personen meist ihr verletztes Bein weniger belasten und somit ein erhöhtes Risiko einer Asymmetrie besteht. Eine andauernde Asymmetrie in der Beinkraftverteilung kann zu vorzeitiger Ermüdung, sowie zu verschlechterter Leistung führen und erhöht weiters das Verletzungsrisiko.

Bei der Anwendung fährt der Benutzer in der realen Welt mit einem stationären Fahrrad und trägt dabei ein Head Mounted Display (HMD). In der VR Umgebung fährt der Benutzer ein Tretboot das durch die gemessene Beinkraftverteilung des rechten und linken Beines gelenkt wird. Gemessen wird mit einem Pedal basierten Leistungsmesser (Garmin Vector 3). Die Anwendung enthält neben den eigentlichen Analysetest, bei dem der Benutzer nur geradeaus fahren soll, einen zweiten Kurs, bei dem der Benutzer einen Slalom fährt. Für beide Kurse gibt es verschiedene Schwierigkeitsstufen, um besser auf den Benutzer eingehen zu können. Die Fahrradanalyse hat eine Dauer von etwa 14-25 Minuten, abhängig von der Leistung am stationären Fahrrad. Diese Arbeit umfasst Beschreibungen zu allen verwendeten Hardwareteilen und die Unterschiede zu existierenden VR Fahrradanwendungen. Weitere Teile dieser Arbeit sind die Erklärung des Software- und Hardware-Designs, Details zur Implementierung und deren visuelle Ergebnisse, sowie die Beschreibung und Evaluierung einer Benutzerstudie.

Die durchgeführte Benutzerstudie hat gezeigt, dass sich Asymmetrien in der Beinkraftverteilung durch die Anwendung erkennen lassen. Diese werden meist während der Anwendung vom Benutzer selbst entdeckt. Da jeder Teilnehmer den Test nur einmal fuhr, lässt sich keine Aussage treffen, ob häufigere Nutzung zur Verbesserung führt. Der Analysetest wurde als effektiv, körperlich anstrengend und unterhaltsam beschrieben.

Abstract

Virtual Reality is an upcoming topic, in which increasingly better hardware enables the realisation of realistic applications. The virtual 3D environment gives the opportunity for visual feedback.

In this diploma thesis, visual feedback should be used in an application to show a user if his right and left leg power is equally distributed. Furthermore, the application should serve to improve a possible asymmetry in the leg power distribution through frequently usage. The application was developed for the use in the field of physiotherapy, especially for people with leg, knee or foot injuries and after surgery in one of these areas, as affected people usually put less strain on their injured leg and therefore a higher risk of an asymmetry consists. A persistent asymmetry in the leg power distribution can lead to premature fatigue, as well as to a worse performance and it furthermore increases the risk of injury.

During the test, the user is riding a stationary bike in real world and is wearing a Head Mounted Display (HMD). In the VR environment the user is driving a pedal boat, which is steered by the measured leg power distribution of the right and left leg. The measurements are taken with a pedal-based power meter (Garmin Vector 3). In addition to the actual analysis test, where the user should only drive straight ahead, the application contains a second course, where the user drives a slalom. Different difficulty levels exist for both courses to better meet the users' needs. The bicycle analysis has a duration of ~14-25 minutes, depending on the performance on the stationary bike. This work includes descriptions of all hardware components and the differences to existing VR bicycle applications. Further parts of this work are the explanation of the software and hardware design, details of the implementation and their visual results, as well as the description and evaluation of a user study.

The performed user study showed that asymmetry in the leg power distribution can be recognized through this application. These are mostly discovered by the user himself during the usage. As every participant took the test only once, no statement can be done whether a frequently usage leads to an improvement. The analysis test was described as effective, physically demanding and entertaining.

Contents

CHAPTER 1

Introduction

1.1 Motivation

A survey showed that in 2017, 34% of the interviewed Austrians are driving their bicycle several times per week, 30% several times per month and only 5% less than a number of times per year, as can be seen in Figure 1.1. As this statistic shows, the frequency of cycling in everyday life is relatively high. Therefore an even distribution of the right and left pedal force is important, as pedalling asymmetry can alter the cycling performance and can lead to premature fatigue and knee or muscle overuse injuries [BAP12]. A simulation program would be helpful to recognize and reduce such an imbalance.

A lot of bicycle applications exist and some of them are already in Virtual Reality (VR). A part of them are using stationary bikes with sensors to measure the actual power and cadence and transmit them to the application to control the velocity for moving forward. Stationary bikes include all types of ergometers, hometrainers or training bikes that are standing still and can therefore be used indoors. Most of these existing biking applications are games and their main benefit is to train indoors with virtual reality and having fun. However, none of the existing biking applications measure the leg power distribution and neither returns this through visual feedback.

To measure power and cadence, which is mostly used in the existing biking applications, only one crank arm or one pedal-sensor needs to record data, but to show the distribution between the right and left pedal force a power meter is necessary, which is able to get data from both pedals, i.e. the Garmin Vector 3. This power meter was released in 2017 and can measure the balance and the pedalling smoothness and would be therefore convenient for the planned VR game. As these dual-sided measurements are rather new, they are rare or not existing at all in applications, especially in Virtual Reality.

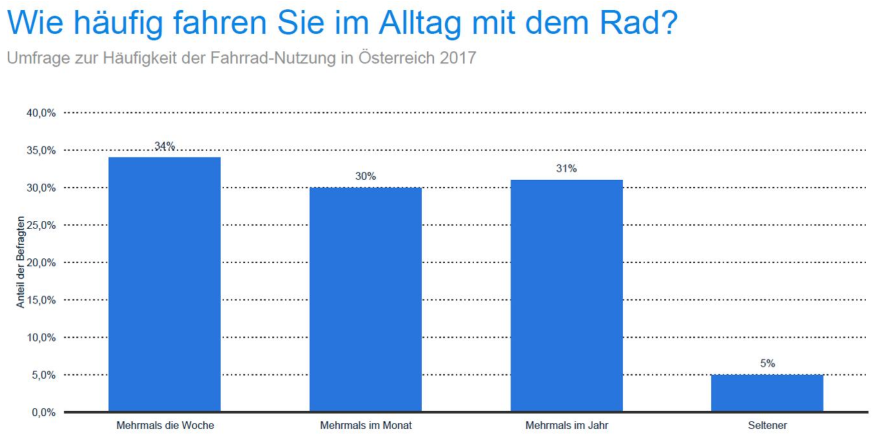


Figure 1.1: This figure shows a statistic of the frequency of cycling in everyday life in Austria. [Kor20]

1.2 Aim of Work

The aim of this work is to provide an application which is able to measure the leg power distribution of both legs and give visual feedback of it during a virtual reality game experience. With the visual feedback, the user can see his bilateral asymmetry and train to get a 50/50 ratio for the leg power. The application is a serious game, which means the usage should further make fun.

The main use case of the VR application was meant for patients with knee injuries or after knee surgery, as they can use the application in their rehabilitation to see how their pedal force on the injured leg changed and to retrieve an equal distribution with the help of the visual feedback. However, as due to COVID19 the application cannot be tested with patients in their physical rehab, an advantage of the application is that it is also useful for professional and hobby cyclists. This is confirmed in a user study by Bini et al., which showed a strong relationship between bilateral asymmetries and performances [BH15].

The user is cycling on an ergometer in real world, and driving a pedal boat in virtual reality. A pedal boat gives a good opportunity to visualize an unequally distributed leg power by steering the boat to the left and right side.

The dual-sided cycling power analysis is a serious game with two different courses and three difficulty levels per course, to best meet the user's needs. The velocity of the pedal boat is controlled with the pedal power generated on a stationary bike and the steering is done with the left and right pedal force. In the first course the user should drive straight forward and try to avoid collisions with the buoy-chains, which restrict the course on both sides. The difficulty level changes the wide of the route. In the second course the user needs to alternate the pedal force of the right and left leg to drive through a slalom. In a higher difficulty level the buoys of the slalom are closer to each other. The test will have a duration of 15-25 minutes, depending on the cycling speed.

The application is meant to be used repeatedly during rehabilitation to see changes and improvements from the beginning to the end of the physical rehab, therefore it gives the possibility to train straining both legs (the injured and the normal one) the same. The analysis test should be supervised by an observer, sitting next to the user and monitor him on the computer, although the patient in Virtual Reality and the observer on his monitor will not see exactly the same. The observer is able to change settings on the computer during the test, e.g. give an offset to one leg if there is a too big disparity between the pedal forces or change the level of difficulty. However, the user should not see any settings to get a fully immersive VR experience, but he has a display, where he can see the actual values of speed, power and the power distribution on different tachometers. The display also shows the reached distance compared to the total distance for this course and the count of collisions or if the user drove in the wrong direction. Further, after each test a PDF-document with all measurements will be created to better compare the results during the whole recovery phase.

A further aim was to find out, if patients feel more comfortable with training in the virtual reality environment than in a training room, next to the medical specialists observing them. A test phase with real patients in collaboration with the physiotherapy department of the FH Campus Vienna was planned, but is not possible due to COVID19. Therefore, there are only a few tests with private persons to get overall feedback on the application and to detect if asymmetry leg power distribution occurs in uninjured or in recovered users with an earlier leg injury and if they are able to compensate this during the test.

1.3 Methodological Approach

The methodological approach can be divided in three main parts. The first part is to get the measurements from the power meter, i.e. the Garmin Vector 3 pedals, which are mounted on the stationary bike, in the game engine *Unity*. The sensors are able to communicate over an ANT+ connection or using the integrated bluetooth smart sensor. For the ANT+ connection an ANT+ stick will be needed, to transfer the data via the wireless network. After comparing some user feedback on diverse internet pages according to the different connections, we choose the ANT+ connection for this application. A further reason for this choice was the application "Advanced ANT+" from the Unity asset store, which is very helpful, as it builds the basic connection from the sensors to Unity. It provides a demo application, where a display already shows the power and the cadence when driving the stationary bike. The next step was to get the left/right balance values through reading the corresponding bytes out of the sensors. Therefore it was important to know how the pedals communicate with each other. As can be seen in Figure 1.2 the communication between the left and right pedal is achieved using an ANT+ private key and afterwards only the right pedal gives the information to the display over an normal ANT+ connection. This and further necessary information of how to transfer the data are described in the ANT+ device profile for bicycle power, which can just be

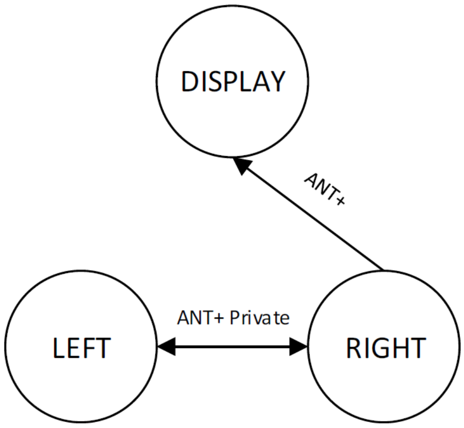


Figure 1.2: This figure shows the communication between the pedals and the display. [Inc20]

downloaded after registration on the ANT homepage [Inc20].

The next part is the implementation of the whole application. This will be done in Unity 2019.3 and with C# for the scripts. The first step in this part is the generation of the terrain with Gaia, where a broad river in the middle of the terrain is necessary for the pedal boat analysis test. The next step is to find models in the internet or create some with *Maya 2019*, when there is no convenient free model available. Some models are created completely new, e.g. the buoy-chains or the start and end banner, others just needed to get modified, like the pedal boat, which was for two persons originally (Figure 1.3). Afterwards, the game logic was implemented, which is dependent on the chosen course and difficulty level. The most important step is an accurate steering mechanism of the boat to give the user a realistic feeling of driving a pedal boat in the Virtual Reality environment. Another big part of the implementation is the creation of the settings menu. Some settings should be done at the beginning, like the name of the patient and the name of the observer, the course and difficulty level and the language, where English and German can be chosen. Some settings are relevant for the observer during the game to help the user to achieve satisfying results, e.g. with adding an offset to the weaker leg. This can be done during the game without pausing it. All settings which are done at the beginning can be changed in the pause menu, with the exception of the course choice.

The last part is the testing phase. Due to COVID19 the testing phase cannot take place with real patients with knee or leg injuries, but as some feedback for the application is important, it will be tested with private persons. After the tests a questioning will be done. This feedback will then be evaluated and analysed. The test group will include some persons which had knee or leg problems in the past. One interesting analysis can be to compare these people with normal users of the test group to find out if there is a higher appearance of asymmetry if they had former leg or knee injuries.

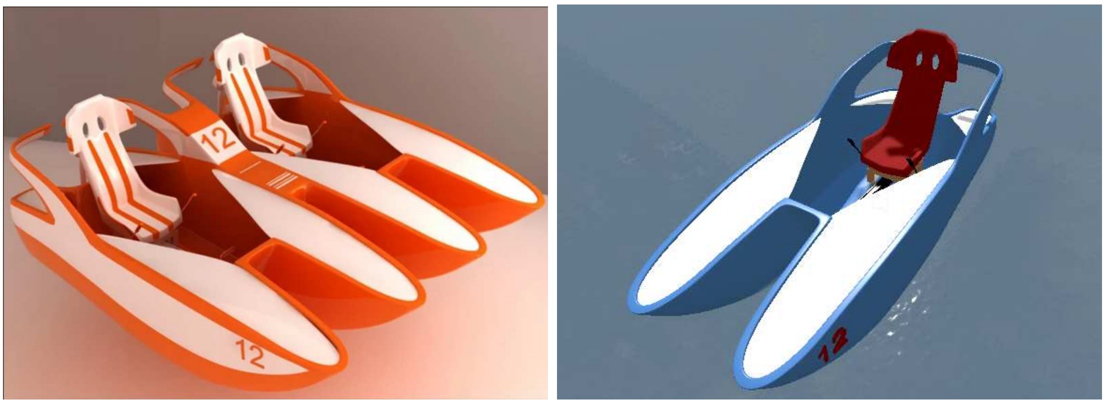


Figure 1.3: The pedal boat model before (left) and after (right) editing.

1.4 Structure of the Work

In the next chapter (chapter 2) some background information are explained. It starts with a description of the overall topic *Virtual Reality* and the functions of the used power meter *Garmin Vector 3*. Later in this chapter, some related work is mentioned including applications with stationary bikes and power measurements. The last part contains a discussion of VR in the area of physical therapy.

In chapter 3 the theoretical background of the application will be described. First the hardware setup will be explained, which consists of several components and afterwards the software design is clarified.

In the following chapter 4, the implementation of the application is described in detail. The first section explains how to transfer the sensor data from the power meter to Unity and how to read out the correct data bytes. The steering of the pedal boat is described, as well as the different courses and difficulty levels. Furthermore, the possible settings for the observer are explained and in the last part the environment of the application is described.

The chapter 5 covers the results of the implementation and evaluation of the user study. In the first section the user study is explained and the evaluation results are described, including comparisons of measurements of the users and the user feedback. Before the results are discussed in chapter 6, some known problems are specified.

The final chapter (chapter 7 gives a conclusion of the thesis and an outlook into the future work in this area.

CHAPTER 2

Background and Related Work

2.1 Virtual Reality

Virtual Reality (VR) refers to the use of three-dimensional displays and interaction devices to explore immersive, real-time computer-generated environments [Bry93]. The history of VR started in the 60's when Ivan Sutherland wrote a paper called *The Ultimate Display* to his research about immersive technologies [DBGJ13]. The term *Virtual Reality* was much later introduced by Jaron Lanier in 1987. Nowadays Virtual Reality is still designated as "young scientific area" and its further development is heavily dependent on the available hardware. Started with the release of the Oculus Rift in 2013 there exists now a lot of high-end low-cost data glasses (e.g. HTC Vive, PlayStation VR, etc.) [DBGJ13].

2.1.1 VR as a Human Machine Interface

Virtual Reality realizes a human-machine interface. The VR environment can be designed in a natural and intuitive way, such that the user can act like he would do in real world. In the best case scenario the user blends out that he interacts with a computer program [DBGJ13]. VR enables an easier way to understand data, as data can be shown in detail in 3D. In Virtual Reality the user is completely separated from his real environment and he can only see the virtual world, as opposed to Augmented Reality where real and virtual images are overlaid. A comparison of the interaction-model with a PC in 2D, in VR and in AR can be seen in Figure 2.1.

Virtual Reality is used across a vast range of applications in the scope of education, medicine, psychotherapy, sports, industry, travel, etc [SSV16]. Some areas of application are now explained in more detail. Virtual Reality is useful in the area of education, as the students can learn by "doing" something on their own and not just observing the

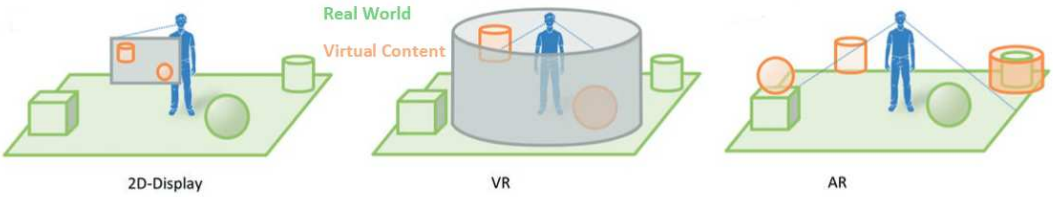


Figure 2.1: Interaction with a PC in 2D (left), in VR(middle)and in AR(right) [DBGJ13].

teachers. Furthermore, abstract entities are changed into tangible property, which is especially helpful in subjects like mathematics.

Another area where VR applications are often used is medicine. Medicine has many different aspects, where the usage of VR makes sense. One aspect is the surgical training, where simulations are used for planning, training and teaching surgery. In interventional cardiology, for example, VR is currently the only satisfactory training strategy when learning on patients [GRC+05]. Another aspect is the doctor-patient interaction. VR provides the possibility to train with virtual patients and gain experience, as experience in different scenarios is necessary to estimate a situation, for example when a patient demands a certain medicine [SSV16]. A further medicine area, often using VR, is therapy, where patients' phobias can be treated through simulating spiders for arachnophobia or simulating an abyss when they have acrophobia [DBGJ13].

Furthermore, VR is used in sports. VR sport applications are often games, therefore the user can learn and train different kinds of sports and further have fun when playing the games. For professional sports it is important to check the differences between the VR and the real version, as just small disparities can lead to incorrect learning.

VR is further used in social psychology for social and cultural experiences in studies, which are impossible in reality for practical or ethical reasons. VR can provide insights into discrimination, for example when placing light-skinned people in a dark-skinned body. Another advantage is that VR allows an exact repetition of an experiment (same conditions for all trials).

Industries use Virtual Reality for training and maintenance, to develop products and inventing new methods of manufacturing. It can be used in all kinds of industry, but especially car manufacture is known for it. Cars can be designed in VR, tested with clients and can be changed flexible, which saves a lot of costs.

These are some of the most popular areas of application in Virtual Reality. The field of VR is changing extremely rapidly and there are new ideas of VR applications every day [SSV16].

2.1.2 Immersion

An overall goal when developing Virtual Reality applications is immersion, which describes the feeling of being inside the virtual environment [YK19]. The level of immersion depends on good VR content and the usage of suited hardware. Of course, a Head Mounted Display (HMD) VR set up gives a more immersive feeling than a traditional 2D screen, as the user is completely surrounded by the VR environment, therefore a distinction of different levels of immersion, depending on the used hardware can be done. Non-immersive systems are the cheapest and simplest type. In these systems the VR applications use desktops to reproduce images of the world [CGRR18]. Full immersive systems use several sensory output devices, like a head mounted display, which means the user is surrounded by the virtual environment. Semi-immersive systems lie between the two already mentioned ones. An example is the Fish Tank VR, which is a stereo image of a three dimensional scene, viewed on a monitor using a perspective projection and coupled to the head position of the observer [WAB93].

The immersion affects the user's presence, arousal and the enjoyment of the game. Furthermore a study by Yao et al. [YK19] proved, that the physical exercising performance increases with the level of immersion (this study is further described in subsection 2.4.3). The terms presence and immersion are closely related, but need to be differentiated. According to Slater et al. [SW97] presence is subjective and describes the state of consciousness, the feeling of being in the virtual environment, as opposed to immersion, which is an objective and quantifiable description of what any particular system does provide or with other words: the quality of this VR experience. The sense of presence can be seen as the outcome of immersion.

The immersion in a virtual environment can contribute to user's need satisfaction, together with other features including the active physical interaction with the virtual environment and the game mechanics. According to Ijaz et al. [IAWC20] a very immersive nature of VR environments can influence the motivation and enjoyment of users. Therefore, a friendly and realistic environment is important, as users of the dual-sided cycling power VR game should be motivated to perform the analysis test without collisions.

2.1.3 Head Mounted Display

For the dual-sided cycling power VR game, a Head Mounted Display (HMD) is used. A HMD is worn on the head, so that the VR-glasses are in front of the users' eyes. The HMD is combined with a tracking system to detect the position of the user in real world and update accordingly the gaze direction and gaze position of the virtual camera [DBGJ13]. Additionally to the VR glasses there are VR-Controllers. The HTC Vive is the HMD used in our application. Next to the headset the system consists of two wireless controllers (which are not used in our application) for realistic HD haptic feedback and two base stations to cover a 360 degree tracking area. The tracking technology is called Lighthouse and works with infrared (IR) [Luc18]. The room-scale of the tracked area is approximately 3.5m x 3.5m. With the HTC Vive headset, the user has a field of view of

110 degrees, a resolution of 1080 x 1200 pixels per eye and an integrated microphone. The interpupillary distance and lens distance can be adjusted [Cor20].

2.2 Power Meters

A power meter is a very useful device that can be mounted on a bicycle to measure the cyclists' power output. It records data during a ride, which can then be downloaded to a compatible device. With this information the cyclist can monitor his training and race performances, analyse his ride, track changes and improvements over any period of time and define weaknesses. Through this knowledge he can modify his training and refocus on those weak areas [AC12].

A power meter measures the power (p) given in watt, which is a product of force (f) and velocity (v) ($p = f \cdot v$). The velocity is calculated by the cadence (with the exception of hub-based systems), given in revolutions per minute (RPM), therefore a power meter needs to measure force and cadence. Multiple types of power meter exist, differing in how they derive measurements. The classification of the power meter types is always a little bit different, but mostly the methods can be divided in six types: a pedal-based system, a hub-based system, a crank arm-based system, a crank-based system, a bottom-bracket sensor and opposing force technology [AC12]. They can be seen in Figure 2.2. In the following, all types are explained in detail [Cit20].

2.2.1 Types of Power Meters

A pedal-based power meter (e.g. Garmin Vector 2/3/3s, PowerTap P1) enclose the gauge inside the pedal itself. The sensor can be in the right, in the left or, for dual-sided measurement, in both pedals, with independent measurement of each leg. Every pedal-based power meter has a specific cleat system, but currently all known are similar to "LOOK Keo" cleats. This means the user needs to mount the cleats on his cycling shoes to clip in the pedals. An example of such pedals can be seen in Figure 2.2a. An advantage of this type is the easy installation, which also means that the pedals can quickly be moved to another bike. It has to be considered that pedal-based power meters do not exist for mountain bikes.

Hub-based power meters (e.g. PowerTap G3 Hub, which can be seen in Figure 2.2b) incorporate strain gauges in the rear hub. The manufacturer "PowerTap" is the only one producing this system. The velocity is calculated from the wheel rotation and the chain transmit the torque from the force to the hub [PHJ+17]. This means it measures the power through the drive chain and therefore the power-value is slightly less than power measured at the crank. This does not mean that the hub-based power meters are less accurate, it is just a little different kind of how to measure power. It is easy to mount the system on the bike, when the user buys a wheelset with the hub pre-installed, otherwise a bike shop is needed. A hub-based system can easily be moved from bike to bike and it is one of the cheapest power meters.

(a) Pedal-based
Garmin Vector 3

(b) Hub-based
PowerTap G3

(c) Crank arm-based
(left only) - Pioneer

(d) Crank-based
SRM Origin

(e) Bottom-bracket sensor
ROTOR 2INpower DM

(f) Opposing force technology
PowerPod

Figure 2.2: The different types of power meters [Cit20].

Forces in the crank arm are measures by a crank arm-based power meter (e.g. Stages Cycling, Pioneer, 4iii Innovations). It is produced by several manufacturers and can be differed in left-only crank arms and dual-sided crank arms. In the left-only crank arms (Figure 2.2c) the measured power gets doubled to get the total power, which means it assumes that both legs produce the same force. It weighs just 10-20 grams and can be changed easily between bikes, if they have compatible crank sets. The complete crank sets (crank arms, spider and chainrings) attach a second sensor inside the drive-side crank arm. It can measure independent left and right leg power and is therefore more accurate, but of course also more expensive. A disadvantage is also that it is more complicated to change the sensors between bikes. For both types (the left-only and dual-sided crank arm systems) the bike frame needs to be compatible to install it. A different approach of the power measurement has the *InfoCrank* power meter, which also has a sensor on each crank arm, but it is the only one, where the strain gauges is placed within the crank arm. This means the measurements are taken directly in the path of torque, through the tangential force which pushes the bike forwards and not through the twisting of the cranks, like in the other crank arm-based power meters [Cit20].

In crank-based power meters (e.g. SRM Origin, Power2Max NGeco) the sensor is located inside the crank spider. These were the first type of power meters and are still recommended by professional cyclists. An advantage lies in the accuracy and reliability and that cyclists can combine it with the components they like, which means they do not need to change their pedals, like in pedal-based power meters, or their hubs, like in hub-based power meters. It has a weight of 50-250 grams, is more difficult to change between bikes and has a slightly higher price. An example can be seen in Figure 2.2d.

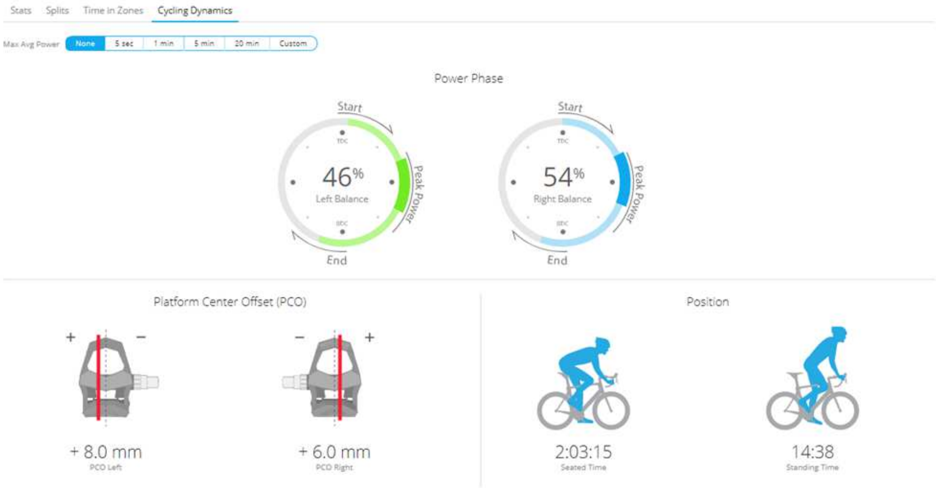
A bottom-bracket sensor (e.g. Rotor 2INpower DM, Eason & Race Face CINCH) is similar to crank-based power meters, but has a different power-measurement location, as it measures torque in the axle. Through this axle-based design the sensor is protected from dirt, water and impact. Further, it is more affordable than other power meters. Dependent on the specific sensor, it measures the total power and left/right leg power independently (Figure 2.2e) or the left side only. They are not meant to swap them from bike to bike.

Opposing force technology measures the power through the forces that oppose the rider. An example is the *PowerPod* (Figure 2.2f) of the company "Velocomp", where the power meter is mounted on the handlebar. It is, unlike to all systems described above, not a direct force power meter. To measure power it uses an accelerometer, a wind pressure sensor, an elevation sensor and a speed sensor. It is the most affordable power meter and easy to swap between bikes, but it requires an additional speed or speed/cadence sensor, which is a sensor measuring the speed through the bicycle's wheel rotation. Furthermore, it is less accurate than direct force power meters.

The pedal-based power meter Garmin Vector 3 is used in our application. The dual-sided measurements of this system are used by cyclists to improve the performance through the knowledge of the leg power distribution. If asymmetry in the right and left leg power exists, the cyclist can train to strain both legs the same. In our application we use the dual-sided measurement to help patients in physical therapy after knee injuries or surgery. The power and cadence are given in the pedal boat analysis test, but are not so relevant for the user. The main purpose is, that the user concentrates on the equal distribution and thereby steers the boat straight ahead.

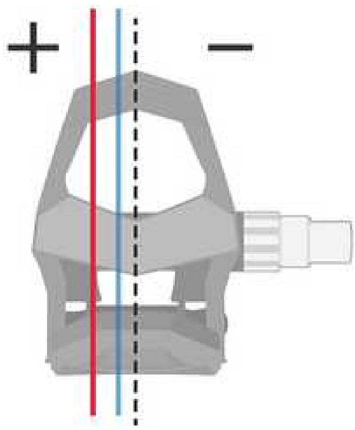
2.2.2 Reliability of Power Meters

Dual-sided measurements are rather new and as such power meters will be often used by sport scientists and cyclists, their accuracy and reliability need to be proved. In a study by Worn et al. [WD19] these characteristics of force measurements, specified by bicycle power meters, were determined. The results showed that crank systems measure crank angle and crank forces with high accuracy and reliability. A review of the Garmin Vector 3 (GV3) pedals shows, that the accuracy (1%) is twice as high as of the Vector 2 pedals (2%) [Stu20]. The GV3 needs a manual zero, also called zero offset, to adapt to weather changes. It is important that this is done for every ride and with the appropriate temperature, otherwise there can be much more loss of accuracy. Hunter Allen, co-author of the book "Training and Racing with a Power Meter" [AC12] came to the conclusion that single-sided power meter gave false results, as he thinks that the power values of both legs fluctuate in a different way. According to Allen, real values can just be measured when the right and left leg are truly separated and both legs measure the output. Combined left/right measurements (e.g. in SRM and P2Max power meter) cannot give as good



(a) Cycling Dynamics data

(b) Power Phase



(c) Platform Center Offset

Figure 2.3: (a) A screenshot of the Cycling Dynamics data on the Garmin Connect Web Software, which shows all additional measurements. An explanation of the power phase graphic is shown in image (b), with examples for the left and right leg. (c) The graphic of the Platform Center Offset, without the exactly values given. The red line shows the average of the current 10 seconds and the blue line the 30-second average value [Ltd20a].

results as the true left and right power meters, which are the Garmin Vector 3 pedals, the PowerTap pedals or the Pioneer crank.

2.3 Garmin Vector 3

2.3.1 Features of Garmin Vector 3

The power meter *Garmin Vector 3/3s* (GV3/GV3s) were released in September 2017. The difference between GV3 and GV3s is that the latter one has just one sensor in the left pedal, whereas the GV3 has a dual sensor integrated, which means both pedals measure the performance. This further allows the measurement of more detailed data, like the balance between the leg forces. The pedals have an ergonomic design and weigh just 322 gram, when the two batteries (of type LR44/SR44) per pedal are already built-in. The precision of measurements amount to +/-1%. The pedals can be connected over ant ANT+ or a Bluetooth LE connection to compatible Garmin Edge bicycle computers or the Garmin Connect Mobile app [gar18]. An advantage of this power meter to other ones is the simple mount on the bicycle, as everything necessary is in the pedals and there are no additional sensors needed. This further means, the user can quickly change between two bikes by unfastening the pedals from a bike and putting it on another one.

2.3.2 Cycling Dynamics

Cycling Dynamics is a term introduced by Garmin. It describes the extended data that can be measured during a ride with a dual-sided Garmin power meter. This data is then transmitted to a compatible Garmin device and shown on the Cycling Dynamics data site [Ltd20b], like can be seen in Figure 2.3a. It gives a deeper insight in the bicycle training and show changes in the performance [Ltd20a]. Furthermore, it allows several new measurements, which are now explained in detail.

- Seated/Standing Position: With cycling dynamics the position of the cyclist i.e. seated or standing, can be determined. It returns how often and how long the user has been in this position, calculated by comparing the applied forces.
- Power Phase: The Power Phase (PP) shows the user in which angle of one pedal stroke he reaches the most power, which can be seen in Figure 2.3b. It calculates the arc length from the power phase starting angle to the end angle.
- Platform Center Offset: Another measured value is the Platform Center Offset (PCO), which shows the user the relation of the applied force to the center of the pedal platform and how the distribution over a specific period looks like (Figure 2.3c). This tool is helpful to avoid injuries and support rehabilitation. PCO is shown in millimetre and returns positive values if there is an increased force toward the outside of the pedal and negative values when the force is toward the inside of the pedal.
- Right/Left Balance: Another additional measurement of the dual sensor is the right/left balance, which is given in percent and is used in our application. This value informs the user if one leg is producing more power than the other one. For

(a) Different games of VZfit Play. (b) Display of Zwift, during a race.

Figure 2.4: Sample bicycle applications using stationary bikes with sensors as input values for moving forward in the game.

cyclists it is good to know if there is a significant asymmetry, to train against it and improve the imbalance, as it can cause premature fatigue and increases the risk of injury.

2.4 Usage of Stationary Bikes with Power Meters in VR

As already mentioned in section 1.1, some biking applications exist, where stationary bikes (i.e. ergometers, hometrainers, not moving training bikes) with sensors are used to measure power and cadence for the movement in the application. The purpose of these applications is the possibility to train indoor in a VR environment, which mostly visualizes an outdoor scene, other applications are to increase motivation and give more power to result in a better performance.

2.4.1 VZfit Play

One well-known application in this area using Virtual Reality is *VZfit Play*, which was earlier known as *VirZoom Arcade* and was renamed in August 2019. It is a collection of several virtual reality mini-games, where the user can be part of a car race, riding a horse, flying a helicopter and many more (samples in Figure 2.4a). With the new name they added additional features and applications like the VZfit Explorer. In this app the user can ride anywhere in the world by entering the address of the desired location and get teleported to it. Necessary to use VZfit is a free or premium membership, a VR headset (Oculus Go and Oculus Quest supported), a bike, a sensor to travel through the virtual worlds (i.e. smart bike, smart trainer or Bluetooth Cadence or Speed sensor) and the controller of the VR headset or a media button. All compatible devices can be found on the VirZoom homepage [Vir19]. Earlier they had their own Smart Bike "VirZoom Bike", but it is no longer available.

In Zeng et al. [ZPG17] a user study was realized to compare physiological and psychological responses of an experience with VirZoom and traditional stationary cycling. The twelve students with a mean age of 25 completed both 20-minute exercise sessions. The VirZoom Arcade games *Race Car* and *Le Tour* were used, as they were observed to be the most intense. Through pedalling the users are driving forward and by leaning their body left and right they can steer their character in the game. Taken measurements are the blood pressure, rating of perceived exertion, self-efficacy and enjoyment. The results showed, that the perceived exertion was higher during traditional stationary cycling and the enjoyment and self-efficacy was significantly higher during the VR-based biking exercise.

2.4.2 Zwift

A famous software platform in this area is *Zwift*, which can be used by cyclists, runners and triathletes. It is known for its big community with over 1 million registered accounts. The main purpose is to train indoor and receive serious results. It is possible to create a customized training plan (by world-class coaches), but there are also plenty of predefined trainings online, organized by time and graded by difficulty, so the user can fit his needs and follow a structured work out. Through the community the users are more motivated as they can cycle together, can take part on multistage tours or Gran Fondos (i.e. bicycle marathons for hobby riders) with other "Zwifters" to every time, day and night. An example of the display during a race can be seen in Figure 2.4b. Further, the users can challenge each other to a sprint or cruise with the pack. The difference to VZfit Play is that Zwift does not use full-immersive Virtual Reality and there are no games, as the focus lies on the cycling performance itself. The application provides ten different worlds with more than 130 routes including roads through the desert or a rise to a volcano. Necessary equipment is a bike, a smart trainer and a technical device like a laptop, a tablet or a smartphone.

VZfit Play and Zwift are just two out of a broad range of cycling applications. Interactive fitness technologies and networks which have real-world activities like cycling and running have increased significantly over recent years (e.g. Strava, Runtastic, MapMyRide, Endomondo, etc.) [Riv20]. But most of these fitness apps just work for a real outdoor cycling tour and measure values by the GPS coordinates without a power meter. A big problem with such physical activity tracking apps is the accuracy of their measurements, as it can vary up to 50% between different models of the same brand and across different manufacturers [KBY20].

2.4.3 Improvement through Usage of VR

In a study by Yao et al. [YK19] the immersion in Virtual Reality games was explored, while riding a stationary bike with and without VR. The participants were divided in

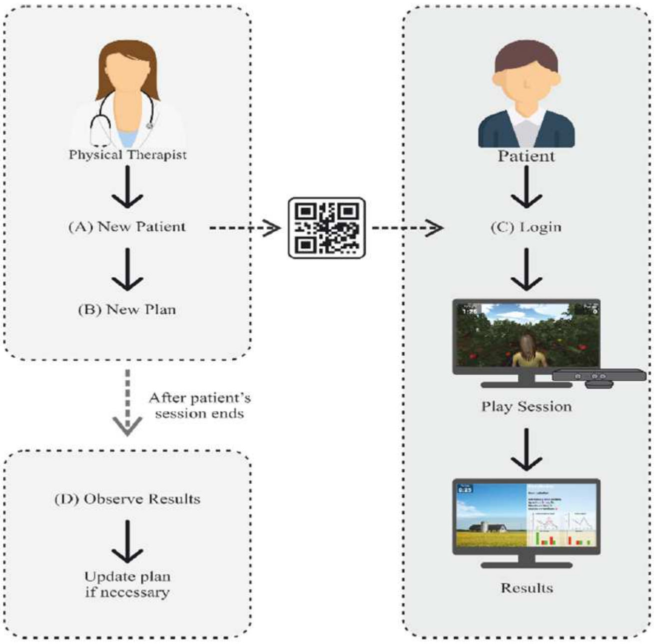


Figure 2.5: The interaction flow of the physical therapist, using a mobile application, and the patient, using the Microsoft Kinect sensor for the serious game [PTC+19].

two groups, which played the same biking game. The non-VR group played with a 2D set up on a flat screen and the VR group with a Head-Mounted Display (i.e. HTC Vive). The 32 participants with a mean age of 22 were divided equally in the two test groups. The input for both groups, which was a VirZoom Arcade bicycle game (subsection 2.4.1), stayed the same to better compare the results. Three kinds of measurements were taken in the study: the *Presence* by using the ITC-SOPI questionnaire [LFKD01], the *Arousal* with the Perceived Arousal Scale [ADD95] and the *Physical Exercise Performance* measured by the distance of travel in kilometer. The results showed, that the travel distance of the VR group (5.45k) was significantly higher than within the non-VR group (5.01k). Furthermore, the presence and the arousal level were higher when using VR and a correlation between these measurements were identified. The study showed that immersive VR experience can lead to better outcome [YK19].

2.5 Virtual Reality in Physical Therapy

A difference of the existing applications described in the last section, to our methodology is that the main focus lies in the usage in the area of physiotherapy, such that users with knee injuries can use this in their physical rehabilitation to learn putting strains on both feet uniformly distributed.

2.5.1 Effectiveness of VR in common Physical Therapy

Virtual Reality is more and more used in physical therapy. It creates new development opportunities in the field of serious games for physiotherapy applications. In Postolache et al. [PTC+19] one of them is presented, based on VR and Kinect as a natural user interface for physical therapy area, especially for upper limb rehabilitation. How the system is working can be seen in Figure 2.5. The physical therapist first creates an entry for the patient with all kind of data, e.g. name, address, date of birth, gender, description, etc. Afterwards, he can create a detailed exercise plan including start/end date, description, duration, level of difficulty and so on. The patient can login by showing the QR code to the sensor and start his exercises. The results of the session are transmitted to the physical therapist on his mobile application, where he can analyse the values and update the exercise plan if necessary. Two types of training sessions exist, the fixed time duration session and the minimum point session. The user has to catch fruits in the serious game, which can be reached with the left, the right or both hands, dependent on the angles of the location of the fruits. Next to the tailored VR game software module there is a smart physio app included, which is used by the physical therapist. The therapist can see session information, including date, points, angles of neck, spine, left/right shoulder and elbows over the time, as well as progress information to better compare the results of the individual sessions. The system, which was tested with 33 students, provides quality improvement in motor rehabilitation, through the possibility to give the user individual training plans to best fit the users' needs.

A direct comparison of virtual reality rehabilitation and conventional rehabilitation was done in a trial by Pazzaglia et al. [PIT+20]. The six week rehab programme involves 51 patients with Parkinson's Disease (PD), which were randomly assigned to the VR and conventional rehabilitation. The conventional programme was performed according to the guidelines for physical therapy in patients with PD, where a session consists of a warm-up, active and cool-down phase. The VR programme contained 7 exercises which take 4 minutes for each and 1 minute rest between them. The results showed, that participants of the VR group had better outcomes in general, especially a greater improvement in balance, walking, arm function and the mental aspect of quality of life [PIT+20].

2.5.2 Effectiveness of VR in Physical Therapy after Knee Surgery

As these studies show, the effectiveness of Virtual Reality-based rehabilitation is given, therefore we now want to focus on proving the effectiveness in physical therapy after knee injuries.

The study of Lee at al. [LSS+16] showed that VR-based games are a good motivational rehabilitation tool for patients after knee surgery. 25 participants, who had a surgical operation, e.g. a total knee replacement arthroplasty, surgical repair or partial meniscectomy (removal of the meniscus), took part on the study. As hardware a Nintendo Wii and the "Balance Board" was used, which is a force sensor (can be seen in Figure 2.6a). The virtual reality rehabilitation contained three categories of game content: yoga content,

(a) Study by Lee et al. [LSS+16] (b) Study by Gokeler et al. [GBM+16]

Figure 2.6: The Virtual Reality environments for the studies with patients (a) after various knee surgery and (b) after ACL reconstruction.

which consists of a "palm tree" and "warrior" session, strength training content with the sessions "balance bridge" and "single-leg extension" and the balance games content including the sessions: Ski Slalom, Tightrope Walk, Penguin Slide and Table Tilt. The study distinguished the importance of varied levels of difficulty to best meet the patients' needs and called this feature the key determinant of immersion. The VR rehabilitation showed a high level of "flow experience", which is in the paper defined as the state, in which people are so involved in an activity that nothing else seems to matter. The participants had different expectations in the different content of the categories. The study confirmed the expectations in its results, as it reported that the training type is more useful for the therapeutic effects and the game type increases the enjoyment and immersion [LSS+16].

Another study was realized by Gokeler et al. [GBM+16], which evaluated the influence of immersion in VR in patients after Anterior Cruciate Ligament (ACL) reconstruction (ACLR). 20 ACLR patients and 20 healthy controls performed a step-down task in VR and non-VR environment, displaying a pedestrian traffic scenario, which can be seen in Figure 2.6b. ACLR patients had a greater alteration in joint biomechanics through the influence of VR. The authors think that the immersion of VR may influence the focus of attention. The patients put less attention to the control of the knee, however, this allows a more efficient movement performance. The study showed that such technologies can help to target altered movement patterns after an ACL reconstruction and further mentioned the importance of finding asymmetrical leg force, as this is a highly predictive factor for risk of second ACL injury. Therefore the measurement of leg power distribution, like in our application, is an important factor after an ACL reconstruction and useful for physical therapy.

2.5.3 Summary

As can be seen from these studies, the usage of Virtual Reality in physical therapy has promising effects. This applies to physical therapy in general, as well as physical therapy after knee injuries. A characteristic that is often detected in the studies is an enhancement of the enjoyment. Further, also a study outside of the physiotherapy area, that treated stationary cycling in Virtual Reality, has shown positive effects. The study by Yao et al. [YK19] showed an improvement of the performance, presence and arousal when the cyclist is surrounded by a virtual environment. The performance, measured in travel distance, of the VR group was in average 440 meters longer than in the non-VR group, which is an improvement of 8.7%. In our application, we use the pedal-based power meter Garmin Vector 3 for another purpose than it is normally used. We measure the right/left balance of the leg power to help patients in physiotherapy after knee injuries to detect a possible asymmetry through visualizing which leg produces more force, by steering a pedal boat in the VR game to the left or right side. This kind of serious game in the area of physical therapy has not been done before. Furthermore, we tried to fulfil the doubts, the users mentioned in the studies, like the necessity of different levels of difficulty and the adjustment to the users' needs, which we do, for example, through helping the user by setting an offset to one foot, if the disparity between the legs is too big.

CHAPTER 3

Design

This chapter contains the hardware and software design of the dual-sided cycling power VR game. In the first section 3.1 all hardware components, their requirements and how we use them are described in detail. In section 3.2 the transmission of the data from the Garmin Vector 3 power meter to the computer over the ANT+ connection is explained. Afterwards the structure and particulars of the main parts of the application are described. In addition, all considerations to the design of the individual points that were made before and partly during the implementation are explained.

The main goal is to create an application, that analyses if users have an unequal distribution in the leg force of the right and left leg. In the VR analysis test the user drives a pedal boat in the virtual world and is riding on a stationary bike in real world. The produced power, measured with a power meter that is mounted on the stationary bike, controls the velocity of the boat in VR. Further, the power meter is able to measure the left and right balance. This value is used to steer the boat to the left and right side, through putting more force on the leg of the desired direction, which means the user is driving to the right side, when he strains the right leg more than the left one. For the development of the pedal boat movement it is important to find a good balance between realness and usefulness. On the one hand, the movement of the pedal boat should feel real to the user, but on the other hand the boat should not shake too much to the sides, as it may do in real world, so that the user does not get sick. Through the steering mechanism it is possible to visualize an asymmetry in the leg force, when the user tries to drive straight forward. As an unequally distribution of the leg force can lead to premature fatigue and injuries it is important that people learn to strain both legs the same. This is especially important for people after a knee or leg injury or surgery, as they normally strain the healthy leg more than the injured one. Therefore the application is mainly designed for patients in their physical therapy to recognize such imbalances and to compensate this through regular training.

3.1 Hardware Setup

For the realization of the application, hardware components from a variety of areas are used. The required equipment for the technical setup is comprehensive. It contains:

- a stationary bike
- a power meter
- a head mounted display
- a computer
- an ANT+ stick

3.1.1 Stationary Bike - "Energetics Magnetic 350 - CT 350"

A stationary bike can be a hometrainer, ergometer or any kind of bicycle that is standing still and is appropriate for indoor cycling. The user is cycling on the stationary bike in real world, to move forward and steer in the application. For our test phase and during the implementation we used a hometrainer called "Magnetic 350 - CT 350", which was produced by the company "ENERGETICS" (Figure 3.1). Since the hometrainer is very old, it can be hardly found on the internet and can easily be confused with the "Energetics CT 350 Ergometer". We preferred a hometrainer instead of an ergometer, as it is much cheaper and for the application completely sufficient. Furthermore, it was available during the COVID19 exit restriction. Hometrainers and ergometers differ in the costs due to the difference in the functionality. Hometrainers have a magnetic brake system and a small wheel that is used to set the level of resistance [Sch17]. This wheel determines, how close the magnet is to the disc flywheel. In our case, we have five different resistive levels. As this system technique is not very complicated, the costs are not very high. An ergometer uses an electromagnetic brake where the user has the possibility to set the power (in Watt) he wants to reach. The resistance is then automatically adjusted to the cadence, which means the user has more resistance when he is cycling slowly and less resistance when the revolutions per minute are high. An advantage of the ergometer is that there are much more setting options, like individual training programs. The conditions of hometrainers and ergometers are determined in the *European Standard EN 957-1* [Sch17].

As the application was not tested with an ergometer, it cannot be guaranteed that it would lead to the same results. However, as the sensors always take the resistance level into account when measuring the power and an ergometer can be used like a hometrainer, the kind of the used stationary bike should not make any difference.

3.1.2 Power Meter - Garmin Vector 3 and Adapters

The used power meter is the pedal-based dual sensor Garmin Vector 3, which was described in detail in section 2.3. The reason for a pedal-based system was the easy

Figure 3.1: The used stationary bike - ENERGETICS Magnetic350 - CT 350. The whole cycling mechanism of the hometrainer is covered.

mount on the stationary bike. Many other types would not have been possible as the crank spider, the hub and in general the most part of the stationary bike, where the mechanism takes place, is covered up by plastic, which can be seen in Figure 3.1. From the range of pedal-based power meters, the Garmin Vector 3 was chosen due to the possibility of independent measurement of the left and right leg power and the general positive feedback on the sensors from many users.

To install the pedals on the bike, the spindle of the pedals normally just needs to get inserted in the crank arm and be tightened by using a pedal wrench. However, in our case an additional adapter was needed, as the power meter (like the most pedals) has a 9/16" x 20 Threads Per Inch (TPI) screw thread and the hometrainer has a 1/2" x 20 TPI screw thread. How this adapter looks like, can be seen in Figure 3.2a. Even tough, the installation of the pedals can be easily done. The adapter just needs to get screwed on the pedals.

The users of this power meter normally are cyclists with special cycling shoes, which are

(a) (b)

Figure 3.2: Necessary add-ons for the GV3. (a) Adapters from 1/2" to 9/16" screw thread. (b) Pedal plates avoid the need of cycling shoes.

necessary, as the pedals have a Look Keo cleat system. Nevertheless, the application should be used in the field of physical therapy and the users, which are normally patients, do not have such shoes. To use the pedals without cycling shoes, pedal plates are necessary that are compatible to the Look Keo cleat system. These pedal plates, which can be seen in Figure 3.2b are clipped on the pedals and build a smooth surface where the user can place his feet. This allows him to wear normal sport shoes during the test. A disadvantage is that the surface of the pedals are relatively small.

3.1.3 Head Mounted Display

The user wears a head mounted display, which is a HTC Vive, to get a full immersive VR experience. This means the user is completely surrounded by the virtual environment. How a head mounted display is designed was already explained in subsection 2.1.3. The two base stations of the HTC Vive system can build a tracking area up to $15m^2$ and the stationary bike should be placed in the middle of it. In our application no controllers will be involved, as they are not essential. The user should fully concentrate on the cycling and it gives him a safer feeling when he can hang on to the handle of the bike. First, it gives the rider more balance and secondly, it helps the cyclist if he gets dizzy. Without controllers, just the position of the head and the gaze direction are tracked, but for our application nothing more is needed.

3.1.4 Computer

To run applications on the HTC Vive, it needs to be connected with a current PC. The requirements for a "vive-ready" computer can be found on the Vive Homepage. The PC is not just necessary to run the application, it is also used by the observer to adjust settings and to monitor the game. Therefore the PC should be next to the stationary bike, such that the observer can monitor the pedal boat analysis test on the computer, as well as the user itself on the bike. The computer used for the implementation and the test phase has an integrated Intel Core i5-8400K processor with 2.81GHz and a memory of 12 GB RAM. As graphic board, the NVIDIA GeForce RTX 2070 is used and the operating system is Microsoft Windows 10 x64. It fulfils all requirements and the application is running smoothly on it.

3.1.5 ANT+ Stick

The dual sided power meter Garmin Vector 3 provides a connection over ANT+ and over Bluetooth Smart. It is not fully clear, if it is possible to transmit the data, especially the Cycling Dynamics data, from the pedals to the computer into the game engine Unity. There are lots of contradictory statements. On the one hand, Garmin wrote on their support page of the GV3 that Cycling Dynamics data can only be transmitted via ANT+ [Ltd20b] to compatible devices. On the other hand, the pedals can be connected via Bluetooth to mobile applications like the "Wahoo Fitness app", where users can record their trainings and analyse the data, including the left/right balance over the time. Due to the concerns that the Bluetooth connection may not work correctly and after reading some user feedback to the different connections, it was decided that ANT+ will be used for this application. A further reason was that ANT+ has a detailed bicycle power device profile description. To create a connection via ANT+ from the pedals to the computer and to transfer the data, an ANT+ stick is needed. The stick is connected to the PC through a USB port and allows the computer to send and receive the ANT+ protocol. USB 1.0 communicates on four different channels and USB 2.0 communicates on eight different channels. As each measurement (e.g. power, cadence) needs its own channel, the USB 2.0 ANT+ dongle is required.

3.2 Software Design

The development of the application can be divided in three main parts, already shortly mentioned in section 1.3. These parts are the transmission of the data to the PC, the implementation of the whole application and the test phase. The first two parts summarize the actual implementation of the application. The software design of these parts with all considerations of the usage will now be explained in detail.

3.2.1 Transmission of Data

The first part is about the transmission of the data from the Garmin Vector 3 pedals to Unity over the ANT+ connection. To get a basic knowledge of the ANT+ data the application "SimulANT+" was used, to simulate an ANT+ display on the computer and transfer the data from the sensors to it. After this worked correctly, the next step was to transmit the sensor data in Unity. The application "Advanced ANT+" from the Unity Asset Store was downloaded for this step, as it builds a basic connection from the sensor to Unity and has furthermore some demos and prefabs included. Especially the "PowerMeterDisplay" script was very helpful, because it already contained the readout of

Parameter	Value	Description
Channel Type	Receive (0x00)	Bi-directional communication is required for calibration and manufacturing purposes.
Network Key	ANT+ Managed Network Key	The ANT+ Managed Network key is not allowed to publish, due to the licensing agreement.
RF Channel Frequency	57 (2457MHz)	This channel is used for the ANT+ bike power sensor.
Transmission Type	0 for pairing	The transmission type must be set to 0 for a pairing search. When it was paired once, the bike should remember the type for future searches.
Device Type	11 (0x0B)	The device type should be set to 11(0x0B) when searching, to pair to an ANT+ bike power sensor.
Device Number	3157	Unique identification of the used bike power sensor.
Channel Period	8182	Data is transmitted every 8182/32768 seconds (approximately 4.0049Hz).
Search Timeout	30 seconds	In the receiver the default search timeout is set to 30 seconds.

Table 3.1: Parameters and values of the channel configuration to transfer the bike power sensor information. Table from [Inc19].

power and cadence. All necessary information for the connection are described in the ANT+ device profile for bicycle power. This PDF document can be downloaded only after registration and confirmation as an ANT+ Adopter [Inc20]. To create a connection and receive data, the ANT channel configurations need to be set. The particular parameters and values, together with a short description can be seen in the Table 3.1. The slave channel configuration is used with channel type "Receive", as only communication in one direction (from the sensor to Unity) is required. The Network Key is necessary for the communication over the ANT+ network and adhere to the ANT+ device profiles. The given device number in the table is the ID of the used sensor in the dual-sided cycling power VR game, the value in general can lie between 1 and 65535. The transmitting sensor contains a 16-bit number that uniquely identifies its transmissions [Inc19]. The

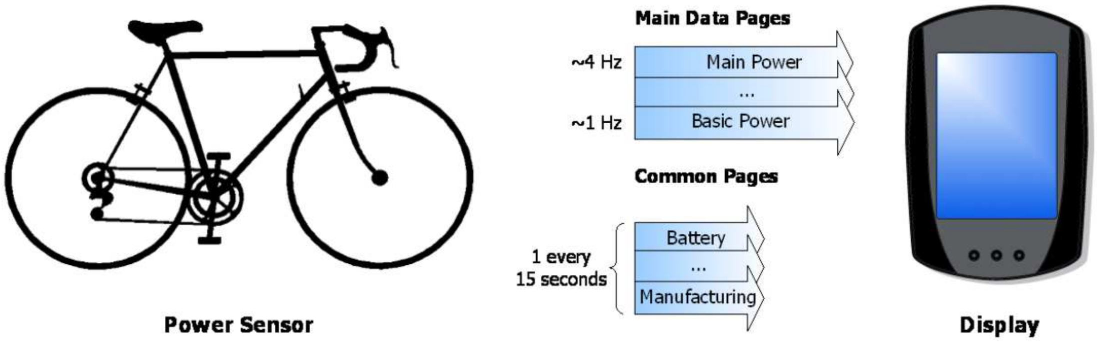


Figure 3.3: Transmission rate of the bike power sensor messages.

device number can be set to zero to allow wildcard matching.

All necessary data can be read out of the "Standard Power-Only Main Data Page (0x10)". How the exactly readout of the data works, will be described in section 4.1, but in general the data page sends messages to the receiver. An advantage is that in Power-Only messages the power and cadence measurements are directly available, without further calculations. All Power-Only messages be updated at regular time intervals. The ANT+ protocol suggests to interleave messages at certain rates. The Power-only messages of the Main Data Page should be interleaved with other messages such that it is sent at least once every 9 messages, but interleaving at least once in every 5 messages is preferred. The transmission rate is depending on the kind of information. As can be seen in Figure 3.3, the main data pages can be divided in main power (transmission rate of ~4 Hz) and in basic power (transmission rate of ~1 Hz). In our application, only the higher rate is used, as the main power contains all essential values, including the pedal power differentiation. The other Cycling Dynamics data from Garmin, like the power phase or the PCO would be part of the basic power with the slower transmission rate. Other messages, which are not critical in time, including the battery status and the device identification are grouped as "common pages" and are sent just once every 15 seconds.

3.2.2 Development in Unity

The application is developed in the game engine Unity (version 2019.3). This developer platform provides great and helpful tools to create real-time 3D content. Furthermore it supports the usage of Virtual Reality. For the handling of the HTC Vive, for example, the free application "SteamVR Plugin" can be downloaded from the Unity Asset Store. It contains many prefab models, like a camera with two controllers, and it is easy to define controller actions. The plugin is not essential in our application, as no controllers are involved. The usage of VR in Unity also works if the setting "Virtual Reality Supported" is checked and the application SteamVR is running on the computer. SteamVR is the tool that runs the HTC Vive HMD and the corresponding system on the computer.

Start Settings

At the beginning of the pedal boat analysis test, the observer, sitting on the computer, should adjust some settings. Some of the settings, including the name of the patient and the observer, are needed for the PDF, which will be created at the end of the pedal boat analysis test. Further the start settings contain the choice of the language (English or German) and the possibility to turn the sound on and off. Sound is an important factor to improve the immersion in VR and should only be turned off in exceptional cases. The most important settings in the start menu are the choice of the course and the difficulty level, which are explained in the next paragraph. The user gets the information that he should wait for the start and in the meantime he can look around to get familiar with the VR environment. The user cannot start driving till the observer presses the start button.

The start menu is just shown to the observer. The idea is that all settings are done by the observer, such that the user can fully concentrate on the test and not get distracted. Furthermore the observer, which should be a physical therapist, can better assess which level of difficulty is appropriate for the user, taking into account his injuries. The observer should rather challenge the user and not set a level that is too easy, just to avoid that the user has any collisions.

Different Views for User and Observer

As already mentioned in section 1.2 the user and the observer should not see exactly the same. The observer can see the view of the user and additionally he is able to adjust some settings during the game. He can pause the game and can change names, the language, the sound and the difficulty level in the pause menu. During the game (without stopping it) he can help the user through setting an offset to one leg, if the asymmetry of the user's leg power is too big and he always collides with the buoy chain on the same side.

The user does not see any settings, to fully concentrate on the analysis test. However, he should have a display where he can see all important values, including power, cadence, the right/left balance, the duration, the reached distance in relation to the total distance, the count of collisions and how often he drove in the wrong direction (in the buoy course). The observer should also get all these measurements. He receives them in an extra window, because otherwise he would just see the values, if the driver looks on his display.

Courses and Difficulty Levels

The application consists of two courses. In the first course, called the "Straight Line Course", the user should drive just straight forward and should try to not collide with the buoy chains on the left and right side. How tight the restrictions on the left and right side are set, depends on the choice of the difficulty level. This course is useful to recognize asymmetries and to train against them, as the user concentrates on an equal leg force distribution to avoid collisions.

Figure 3.4: Comparison of an environment in Unity and with CTS. Image from [Wor19]
.

In the second course, called the "Buoy Course", the user should drive slalom around some buoys placed in the middle of the river. The difficulty level changes the distance between the buoys. The user always gets an information on which side of the buoy he has to drive and he gets a warning, when he drove the wrong way. In addition, the user should try to not collide with the buoys. With this course, the user can train to strain both feet separately. Through the steering around the buoys the user has to alternate the pressure on the feet.

Three difficulty levels exists (i.e. easy, normal, hard) to be able to go into detail on the users' needs. The difficulty level can be changed during the ride. This is important, as an user should not get frustrated when he has many collisions and the course is too hard to drive. The length of the courses are restricted through a start and an end banner. All measurements, which are relevant for the report, are just measured between them. The courses have different starting points and different lengths, where the straight line course is longer, as the user is faster when he is just driving forward. The duration of both courses is between 15 and 30 minutes depending on the power of the user.

Terrain

Unity has an integrated terrain editor, but to get a more natural and realistic environment the scene generation system "Gaia" was used. With this tool from the Unity Asset Store, the terrain can be easily created by stamping mountains, hills, rivers and so on. The application includes different textures (e.g. grass, sand and stone) for the terrain, trees and details like flowers and grass. Furthermore, some models including rocks, farmhouses and accessories (e.g. wagon, fence, wood, hen house) for the landscape can be spawned randomly over the scene. Additionally to Gaia, a further application of the developer company "Procedural Worlds" from the Unity Asset Store was used. It is called Complete Terrain Shader (CTS) and can be used together with Gaia to improve the realness of the terrain. The package includes a Physically Based Rendering (PBR) texture library that can be applied. A big advantage is the possibility to change the scene at run time. Further improvements are the usage of dynamic snow and weather simulations, and that terrains can be tinted by season. A comparison of a terrain created with Unity and improved with CTS can be seen in Figure 3.4. The scene of our application consists of a river, which flows into a lake. The river is surrounded by mountains, hills and trees, so the user cannot see the end of the terrain and has a friendly environment. On the top of the mountains lies snow, generated with the CTS package. No further details are spawned, as they would not been clearly visible from the view of the player (who is on the pedal boat in the middle of the river) and furthermore it would lower the performance.

PDF Report

At the end of each analysis test, as soon as the user passes the end banner, a PDF document will be generated to summarize the measurements during the ride.

The generated document contains basic information, including the name of the patient, the name of the observer and the date, overall settings (e.g. course and difficulty level) and the results. The results are shown in all details, including average values of the left and right pedal force and the count of collisions, subdivided in collisions on the right and left side. The mentioned values are the crucial factors to see, if the user has problems driving straight forward, which further would mean that an asymmetry in the leg force exists. As the document stores all important values, it is also helpful to compare the results when a patient repeats the test and to determine if there is an improvement. It is assumed that improvements are just reached, if the test is repeated more often over a period of time.

The document will also be created when the user cuts the test short. The report will be saved automatically in a folder so that the observer cannot forget to save the document. The document should be saved with the name of the user and the date. It must be ensured that the PDF is not overwritten if the user repeats the test on the same day or if he does the second test.

3.3 Summary

In summary, the equipment is extensive but necessary to implement the application as described. In section 3.1 we justified the choice of our hardware, but if other hardware components would been chosen for the test, some additional hardware, like the screw thread adapter could be omitted.

In the software design it was an important step to understand how the communication over the ANT+ connection takes place. The information of the document "ANT+ device profile for bicycle power" [Inc19] was important to understand the process and to know which configurations are necessary to build the communication channel. How the message is constructed and how the information can be read out will be discussed in the next chapter (section 4.1). For the development of the application in Unity a lot of considerations were done, to provide the user a full immersive VR experience. In this section the creation of the terrain and the used packages for it (i.e. Gaia and CTS) were described. Further discussed points are the start settings of the observer, what the user and the observer can see during the ride, the importance of the courses and difficulty levels and the usefulness of a document which saves all measurements during the ride to compare the results. All of these considerations to the individual points of the application were explained in subsection 3.2.2.

CHAPTER 4

Implementation

This chapter contains the implementation of the application. All the important code parts are explained in detail. This includes the readout of the data from the ANT+ connection, all considerations for the pedal boat (e.g. the design of the display, no water visible in the boat) and its steering mechanism, as well as the set up and length of the courses. In the next section the different displays of the observer are described and all thoughts to the creation of the environment are given. The next section shows the structure and an example of the PDF. In the last section some improvements for the visual quality are shown with details of the application.

4.1 Read Sensor Data

As already mentioned in subsection 3.2.1 the sensor data is readout of the "Standard Power-Only Main Data Page (0x10)" from ANT+. It includes the power, the cadence and the pedal power given in percent. The messages of this page consist of 8 bytes (0-7) and in Table 4.1 is shown, which byte refers to which value. How the readout of the bytes is done in the script can be seen in algorithm 4.1. As the power has a length of 2 bytes, the second byte needs to get left shifted by 8 (algorithm line 3). The variable "bit" (in line 5) stores the 7th bit of the pedal power, which is the pedal differentiation. If this parameter has the value zero, the pedal power contribution is not known and therefore the right and left pedal power cannot be stored. Line 7 excludes that the pedal power has the special value of 255 (0xFF), which would mean that the pedal power is not used. When the right pedal power is stored, the value 128 have to be subtracted, as data[2] includes the 7th bit, which is always set to 1 when this line is called. The right and left pedal power are measured separately by the sensors, but the message only contains the right value as a percentage, as the left one can easily be computed.

Algorithm 4.1: Readout of the bytes from the message.

```
Input: Byte[] data
if data[0] == 0x10 then
    updateEventCount = data[1];
    instantaneousPower = (data[6]) | data[7] « 8;
    instantaneousCadence = data[3];

    var bit = (data[2] & (1 « 8 - 1)) != 0;
    if bit == true then
        if data[2] != 255 then
            rightPedalPower = data[2] - 128;
            leftPedalPower = 100 - rightPedalPower;
        end
    end
end
```

4.2 Pedal Boat and Steering Mechanism

4.2.1 Setup and Details of the Pedal Boat

The model of the used pedal boat was downloaded from the internet and modified with the software "Autodesk Maya", as it was originally designed for two persons. Furthermore, an animation of the pedals were created in this software, as it may feel weird to the user if the pedals are not moving when he is pedalling in real world. Nevertheless, the user would still have a strange feeling, as he cannot see any feet on the pedals. This was counteracted by placing an avatar into the boat. The human avatar was rigged and animated, such that he can sit on the seat and his feet can be placed on the pedals. The animation of the feet and the pedals were coordinated and are both set to the corresponding cadence. This guarantees that the animation of the pedals stops when the user stops pedalling.

The user should have the possibility to orientate himself on his values while driving the test, hence his performance is shown to him on a display, which is placed well visible on the front of the boat. The display should be intuitive and clearly arranged. Therefore we changed the first design, where all measurements were listed one below the other and changed it to a more dynamic display. The improvement from the first design to the actual display can be seen in Figure 4.1. As the new display has another shape, the boat model was modified for it. To show the power, cadence and the right/left balance we used tachometers. The creation of them is done automatically when the observer starts the game. In a script, the min/max values and the desired step length of the power and cadence tachometers are set and a method calculates the text and orientation of the labels and put them on the tachometer. The exact measurements are additionally shown in green font below the tachometers. The most important value (i.e. the right/left

Byte	Description	Length	Value	Units	Range
0	Data Page Number	1 Byte	0x10: Standard Power-Only message	N/A	N/A
1	Update Event Count	1 Byte	Power event count	N/A	256 (Rollover)
2	Pedal Power	1 Byte	Bit 7: Pedal Differentiation 1 - Right Pedal Power Contribution 0 - Unknown Pedal Power Contribution Bits 0-6: Pedal Power Percent Special Values: 0xFF - pedal power not used	%	0-100%
3	Instantaneous Cadence	1 Byte	Crank cadence	RPM	0-254 rpm
6	Instantaneous Power LSB	2 Bytes	Instantaneous power 1-watt resolution	1 Watt	0- 65.535kW
7	Instantaneous Power MSB				

Table 4.1: The message format of the "Standard Power-Only Main Data Page". Containing only the bytes used in our application. Table from [Inc19].

balance) is placed in the middle of the display. This tachometer is shaded with different colours for faster understanding, which leg produces more power on the pedals. In this tachometer the values are ordered differently. When the needle is up in the middle, the user has the desired balance of "50/50", both sides further show the labels from 60-100. Thus, the user can also orientate himself on the needle and does not have to pay attention to the exactly values, which means for example, if the needle is on the right side of the tachometer the right leg is more strained. The display further shows the count of collisions on the bottom left and the count of driven wrong directions on the bottom right (only in the buoy course), illustrated with an icon. The reached distance by comparison to the total distance is shown on a slider and the duration shows the time passed since the start banner.

The pedal boat is placed in the river, so that the engine and the lower part of the boat are in the water. To avoid that water is visible inside the boat, some objects were created and placed over the water surface inside the boat. The objects are rendered with a depth mask shader, where the colour mask is set to zero, which means nothing is drawn in the colour channel, and "ZWrite" is turned on, which means that the pixels are written to the depth buffer. To make sure that the water is not visible within the boat, the objects are set to the end of the geometry render queue.

(a) First display design

(b) Actual display

Figure 4.1: A comparison of (a) the old and (b) the new display for the user, placed on the front of the pedal boat.

Movement and Steering

The movement of the pedal boat is one of the major parts in the application. The movement should feel realistic but the boat should not shake too much, as pedal boats would normally do on the water, to prevent the user from feeling sick. To realize this, the rotation in X and Z direction was at first limited to a maximum of 15 degrees in each direction, but as this still gave the user a weird feeling, the rotation in X and Z were frozen.

The speed of the pedal boat is controlled with the power the user drives on the stationary bike. This is done in the script, through adding a force ($force = forwardVector * power * Time.deltaTime$) to the rigid body of the boat. However, for the right value of the speed it is further important to set appropriate values for other parameters of the rigid body, so that the velocity reaches in average 7 km/h, which is the speed a pedal boat would drive approximately in real world. Therefore, the parameters "mass", "drag" and "angular drag" were changed, till acceptable settings were found. With the values mass:4, drag:0.25 and angular drag:1.5 for the rigid body the user will drive a velocity of 5,688 km/h with a power of 80 Watt and a velocity of 11,412 km/h with a power of 160 Watt.

The left and right leg power is measured in percent. The distribution of the leg power is calculated by the power meter through measuring both legs independently, but only the right value is returned by the sensor, as the left one can easily be computed with the formula: $leftLegPower = 100 - rightLegPower$. The range of the right pedal power [0-100] is than mapped to the range [-1, 1]. To involve the balance measurements into the steering of the boat, a torque was added to the rigid body, where x and z are set to zero and the y value is computed with: $y = mappedValue * (power * 10) * Time.deltaTime$. As the power is involved in the calculation, the steering of the boat is easier when the user drives more slowly. It is assumed, that deviations are small on average, therefore the user already notices a slight "right-hand drive" with a distribution of 49/51 (L/R).

4.3 Courses and Difficulty Levels

Setup of the Courses

The two different courses contain different game objects, therefore the course choice is requested when the observer presses the start button and by this click the objects are set automatically. In the straight line course two buoy chains are needed, restricting the course on the sides, which can be seen in Figure 4.2a. The start and end points of the chains are directly tied with the poles of the banners. A problem occurred when the distance between the chains are getting narrower in the hard and normal difficulty level, but the banner always has the same size or rather the same distance between the poles. To connect the chains with the poles, corners were added to the buoy chains at the start and the end.

The second course contains separate buoys and can be seen in Figure 4.2b. The distance between them are set automatically at the beginning, depending on the difficulty level. On the top of each buoy, there is a flag with an arrow to the left or right. The flags with a left arrow have another colour than the ones, leading the user to the right. This should help the user to recognize the correct side of the buoy from far away. The user should try to not collide with the buoys and he should drive in the right direction, otherwise the information "Wrong Direction" is shown.

The game logic here works as follows: All buoys are stored in a list and if the boat passes one buoy the next one is stored as "nextBuoy". Before the next one from the list is set, it is checked whether the tip of the boat is on the right or left side of the current "nextBuoy" and whether this is correct. Is this not the case, the count of "wrong direction" on the display increases by one and the user gets a red blinking text with this information. To get the impression that the buoys are swimming in the water, their position goes slightly up and down, controlled by a script which adds a force to the rigid body of the buoy ($force = Vector3.up * upValue$). Different "upValues" are used as they should not have the exactly same movement. When the difficulty level is changed during the game, the positions of the objects are newly set and if the pedal boat would be outside of the buoy chains (in the first course) or inside a buoy (in the second course) the boat will be repositioned.

Length of the Courses

Through the knowledge of an experienced physiotherapist, it was told that patients should ride their bicycle in physical therapy for 20 till 30 minutes. The desired duration was lowered to 12-25 minutes, as it is more exhausting when the patients have to wear the head mounted display. The length of the courses was chosen accordingly to reach this duration. In consideration of the calculation of the speed (see section 4.2.1) the

(a) Straight Line Course

(b) Buoy Course

Figure 4.2: The two available courses. (a) The corners in the buoy chains are necessary in the normal and hard difficulty level. (b) The buoy course with the buoys and flags on the top of them to show the side on which the user has to pass the buoy.

lengths were set to 2300 meter for the straight line course and 1800 meter for the buoy course. Therefore the user would have a duration of ~24 minutes when he drives 80 Watt in average, and just ~12 minutes when he drives 160 Watt in average for the straight line course. The duration is more difficult to calculate for the buoy course, as the user is not just driving forward and it is varying from user to user how big the turns around the buoys are taken. Some tests were done to prove if the distance of the course is acceptable for the desired duration with the following results:

- a duration of ~14 minutes, when driving 116 Watt in average
- a duration of ~18 minutes, when driving 85 Watt in average
- a duration of ~21 minutes, when driving 80 Watt in average

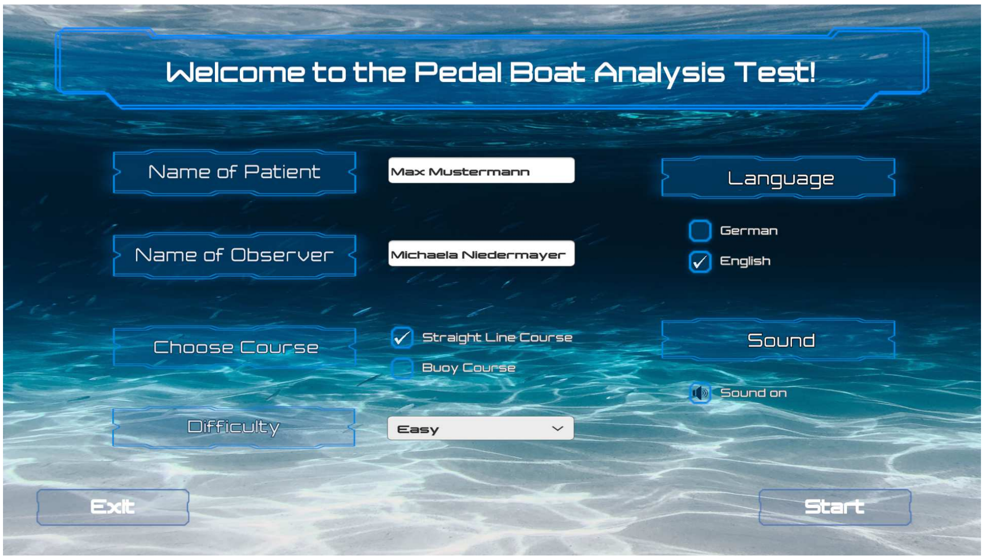
As the results all fulfilled the requirements on the duration, the distance of the buoy course was defined with 1800 meter.

4.4 Settings for Observer

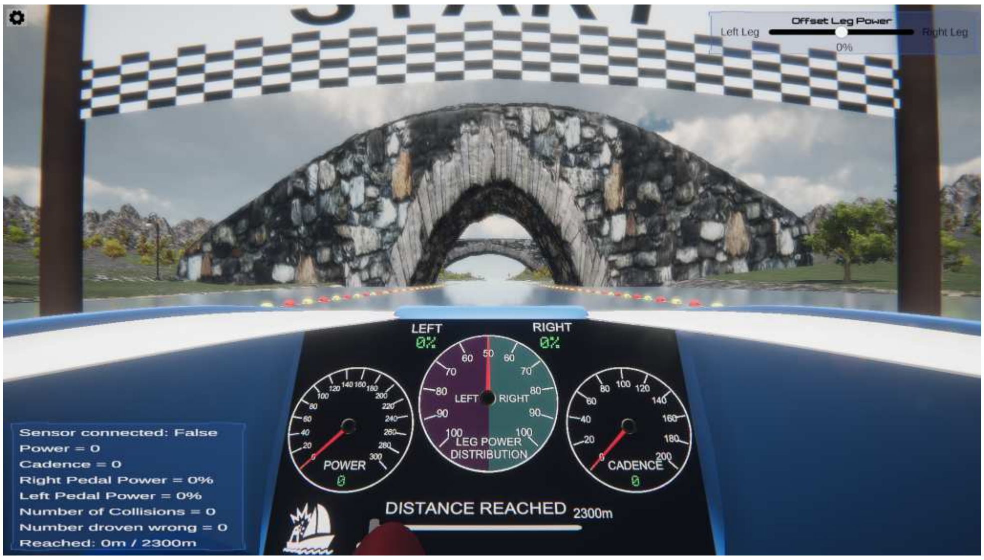
The possible start settings for the observer, which were already listed in subsection 3.2.2 under the category "Start Settings", are now explained in more detail. The display of the start settings, only shown to the observer at the beginning of the application, can be seen in Figure 4.3a. For the creation of the display the package of the Unity Asset Store "Unity Samples:UI" was used, which has some prefabs of good looking graphical user interface components. Some settings, including the sound and the language are changed immediately when the observer toggles them on or off. For changing the language, a script called "ChangeTextLanguage" is added to every "Text" and "TextMeshPro" component in Unity, where the English and German text can be set for it. However, for some components the text needs to be set in other scripts, as they also change their meaning during the game. Some components, e.g. the dropdown menu for the difficulty level, also need a special method to set the language, as all items of the dropdown list refer to the same text component.

Start settings including the course choice and the difficulty level are set when the observer is pressing the start button, as this is the moment, when all required game objects should be visible to the user and hence should be set active. Before pressing start the user can see the environment of the game, but no course dependent objects. Furthermore, the user is surrounded by a cube showing the information "Waiting for Game to Start" on every side. How this looks like, can be seen in Figure 4.4a. When the start button is pressed, the cube is deactivated, game objects are activated and positioned on their defined places (depending on the course) and also the pedal boat is repositioned to the starting point. The view of the user during the test can be seen in Figure 4.4b.

The view of the observer changes too when the start button is pressed. He can now see the view of the user with additional settings. How this monitoring view looks, can be seen in Figure 4.3b. The information of all measurements are in the left bottom corner. They are just listed as the observer does not need such an intuitive display, as the user does. Moreover, the observer gets the information if the sensor is connected. In the top right corner, the observer can adjust an offset to one leg of the leg power distribution with a slider, up to 10 percent on every side. This is done in order to allow the therapist



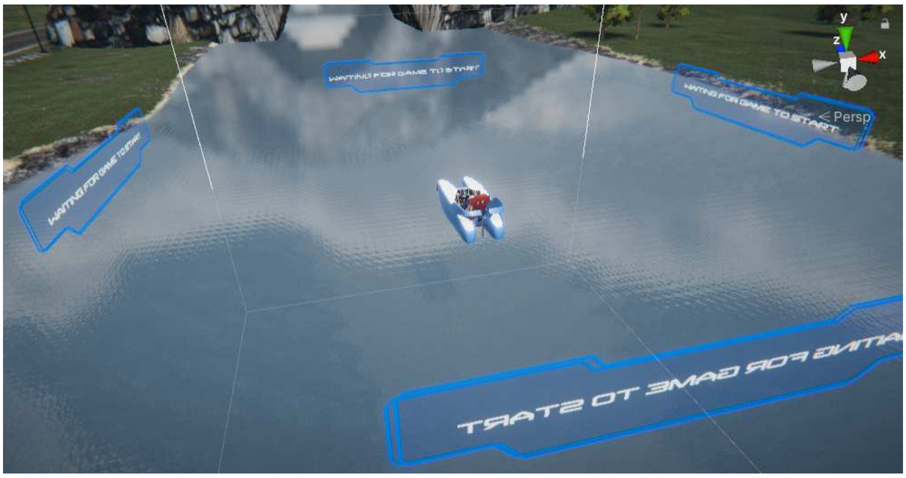
(a) Start Display



(b) Display during Game

Figure 4.3: These are the views of the observer. The start display is shown at the beginning to make some settings for the test. During the game the observer can monitor the measurements of the user and can help him if he is not doing well.

to correct unequal distributed values and thereby support the user. The added offset is included in the calculation of the steering and in the measurements shown to the user on his display, but they are not shown in the results and in the average calculations of the generated PDF report as it would falsify the performance and the knowledge about the leg power distribution would be unusable.



(a) User environment during settings

(b) First Person View

Figure 4.4: (a) The cube that surrounds the user before the game starts. (b) The view of the user during the analysis test.

When the observer presses the settings button on the top left corner, the game is paused. As soon as the button is pressed, all game objects get deactivated and the user can again only see the environment and the surrounding cube. The text information of the cube changes to "Game Paused" on every side. The time scale is set to zero in the code, which stops the game actually. This means the pedal boat stops driving immediately, but all values and forces of the rigid body of the pedal boat stay the same. When the observer resumes the game, the time scale is set back to 1, which is the normal time scale, and the saved forces are reapplied to the pedal boat. During the pause, the observer gets a display similar to the start menu, but without the possibility to select a course. This means the pause of the game can be used to change the level of difficulty, the language, to toggle the sound on or off and to pause the game if the user feels dizzy. Furthermore, some texts of the headers and buttons change, for example the text of the start button "Start" is changing to "Resume".

4.5 Environment in the VR Game

The VR environment should appear friendly and realistic so that the user gets a full immersive experience. The importance of a friendly environment in a VR serious game in the area of rehabilitation was already explained in subsection 2.1.2. The most important thing in the environment is the terrain. It has a size of 4096 x 4096 meter and was generated by diverse stamps from the generation software Gaia. The structure of the terrain can be seen in Figure 4.5. The terrain was changed very often during the implementation. In the first design the river was much wider and the hills around it were all green and smoothed. When the terrain was tested the first time with the HMD, it was decided to make the river smaller, as the user would not see anything from the surrounding environment. In the actual version all surrounding mountains were stamped with the same stamp "Island 1909_2", but as different rotation and sizes of the stamps were used, the mountains do not look the same. The hills did not get smoothed, like in all the other versions, as it makes an unrealistic look. With the included CTS system the mountains were further improved and snow was placed on the top of the mountains. The river was stamped with "River 10" and the lake at the end of the river was generated with the inverted stamp "Blue Diamond Hill". The lake is built like a bay and is surrounded by high rock walls. At the end of the lake is a small beach.

In the environment are two bridges, whereby the user has to drive through below. As can be seen in Figure 4.5 the first bridge is small and stands partially in the water and the second one is broad and the poles are out of the water. Users doing the straight line course drive through both bridges, but as this course is restricted on both sides the narrow passage of the first bridge is no problem. However, in the buoy course the route is not restricted on the sides and therefore the first bridge could be too narrow for the users to drive through. For this reason the starting point in the second course lies behind the first bridge.

Another object in the environment is a road next to the river, which was created with a demo of the package "EasyRoads3D" from the Unity Asset Store. Street lights are placed next to the street at regular intervals, till the end of the road, where it leads into a tunnel. The road is hardly visible from the pedal boat, as the street is flat and slightly higher than the river, but the user will recognize it through the street lamps.

To create a friendlier environment, birds and butterflies were placed in the scene. The

Figure 4.5: The total scene of the VR game environment.

object models and their movement behaviour are from the application "#NVJOB Simple Boids" from the Unity Asset Store. Many settings can be done in the Script and in Unity to control the flock behaviour, e.g. the number of flocks and birds or butterflies, the speed, the scale and so on. The scene includes 5 bird flocks with 150 birds each and 7 butterfly flocks with 3 - 10 butterflies each. The butterfly-flocks are located much lower than the birds. A problem occurred with the prefab of the birds, as they looked completely different as in the preview, although all settings and textures were set to the same values as in the preview. The problem was due to the used *Gamma* colour space. Therefore the colour space in the player settings were changed to *Linear*, which solved the problem.

Besides all the game objects, an important component for a realistic environment is the use of sound. The used background sound is part of the terrain generation system Gaia. It is an environment sound and should simulate the nature in the morning, which means it includes birds chirping and nature sound. Another sound source is a splashing water when the user is driving the boat and a collision sound when the pedal boat collides with another object. As the sound should sound real and should give a realistic feeling, the water splashing is faded in and out when the user starts and stops driving the boat.

4.6 PDF Report

For the PDF report that will be generated at the end of the game "SharpPDF" was imported. It is a C# library used for the creation of 100% compatible PDFs with few steps. The first two things the developer should create when using this library is a "pdfDocument", which builds the real PDF document and is therefore the most important

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VR Fahrrad - Leistungsanalyse

Datum: 24.08.2020 19:04:38
Patient: Petra Niedermayer
Beobachter: Michaela Niedermayer

Allgemeine Einstellungen

Kurswahl:	geradliniger Kurs
Schwierigkeitsgrad am Ende:	Normal (2300m)
Weitere Schwierigkeitsgrade:	-
Schwierigkeit - längste Distanz:	Normal(2300m)

Ergebnisse

Dauer:	0:23:9,84
Distanz:	2300/2300m
Vorzeitiger Stopp:	NEIN
Anzahl an Kollisionen:	2 (Links:2, Rechts:0)
Stärker belastetes Bein:	LINKS

Übersicht

	Rechte Beinkraft	Linke Beinkraft	Leistung	Trittfrequenz
Maximum:	80%	80%	153 Watt	93 RPM*
Minimum:	20%	20%	42 Watt	60 RPM*
Durchschnitt:	49,94%	50,06%	83,66 Watt	72,82 RPM*

*RPM = Anzahl der Umdrehungen (Revolutions per Minute)

Figure 4.6: An example of the generated PDF report in German.

object, and the "pdfPage", which is the base element where the developer has to add further objects like texts, images, paragraphs or tables. The difficulty of creating a PDF within a script is that the X and Y position of every object (e.g. every text line) need to be set manually, as well as the font type and the font size.

An example for a test result in German can be seen in Figure 4.6. Most of the content, including general settings, results and overview are created with a table object, but no boundaries are shown for the first two of them. Another challenge was to add the logo of the Technical University of Vienna in the desired size at the top of the page, as the images are always shown in their original size and cannot be resized. As no logo could be found in the desired size on the internet, an own method was implemented for the "imageElement", where the developer can add the desired width and height, in addition to the original height and width.

The PDF is stored in the folder "PDF_Output", which will be created if it does not exist. Usually assets get combined into a project when it is built, but sometimes assets, e.g. the image of the logo, have to be accessible via a pathname from the script. Therefore the logo needs to be stored in a folder called "StreamingAssets", as Unity copies files from this folder to a particular folder of the same name when building the project.

The measurements for the document start when the boat passes the start banner and end with the finish line. The used difficulties are listed together with the distance driven in that level. "Premature Stop" means that the user did not reached the finish line, as he cuts the test short, and the observer exited the application. The number of collisions is subdivided into left and right side collisions, as this can be an interesting factor for the physical therapist and gives information of a possible asymmetry. Most of the values shown in the PDF are stored during the ride with the exception of the average values. For the average calculations, all measured values of a specific parameter are summed up and are then divided by the number of the events. This is done for the power, the cadence and the right and left leg power. When the user drove the buoy course, the PDF results further show the count of "driven in the wrong direction", which increases when the user drives on the wrong side of the buoy. Apart from that there are no changes for the buoy course, but the observer has to regard that the average values for the left and right leg power are not so meaningful for this course. As it would have been circumstantial to request for the correct language for every text line separately, the creating methods of the tables and the PDF were copied and all the texts were changed to German. Therefore only one language inquiry is necessary at the beginning of the generation, which then calls the appropriate method "CreatePDF" or "CreatePDFGerman".

4.7 Improving Visual Quality

To create a good looking scene it is important that the environment and the camera get post-processed. The camera contains volume blending and anti-aliasing settings in its post-process layer. Through anti-aliasing the graphics have a smoother appearance. As algorithm the Temporal Anti-Aliasing (TAA) is used, which is an advanced technique where frames are stored in a history buffer over time to smooth edges more effectively. This technique requires motion vectors and is more expensive, but it returns graphics in a higher quality. Another setting used is the "Camera Reflection Probe", which is responsible for the fact that the sky and the clouds are reflected in the water and on

(a) Without Rendering Effects (b) With Rendering Effects

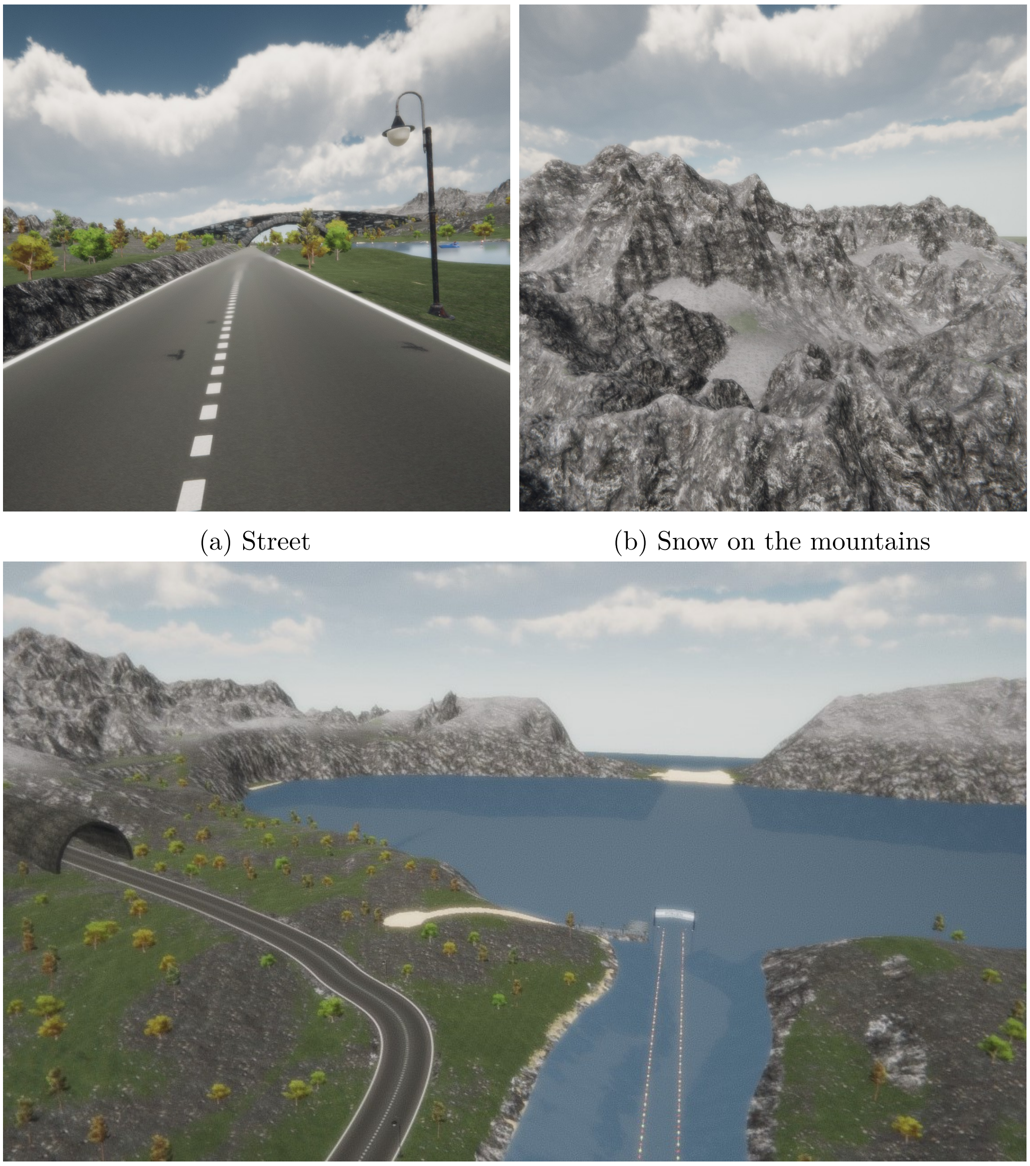
Figure 4.7: A comparison of the scene with and without rendering effects.

the terrain. A big improvement in the lightning of the scene is done through the global post processing that contains a lot of rendering effects, e.g. ambient occlusion, bloom, vignette, motion blur, color grading and so on. All of them improve the visual results, for example the ambient occlusion effect is used to darken surfaces, the bloom effect brings the illusion of a very bright light and the motion blur effect is used when an object is moving faster than the camera's exposure time. The description of all other used rendering effects with their parameters of the post-processing volume can be seen in [Tec19]. How this post processing and reflection effects improve the scene can be seen in Figure 4.7. The figure shows a comparison of a scene part with and without rendering effects.

The most important visual parts of the application, including the start display and the two courses were already shown earlier in this chapter, as they should help for a better understanding of the implementation parts. However, some interesting details, which should especially give impressions of the realness of the scene, are not shown yet.

One of this details was possible to generate by improving the terrain with the usage of Complete Terrain Shader (CTS). With this package it was able to add snow on the top of the mountains. For this feature the minimum height and the angle of the snow can be set, which assured that the snow is only on the top of the mountains. How this looks like can be seen in Figure 4.8b. In Figure 4.8a the street located next to river can be seen with shadows of some birds on it. Street lights have also been added so that the user can recognize the road from the perspective of the pedal boat. The tunnel at the end of the street can be seen on the left in Figure 4.8c. In this image the lake at the end of the pedal boat analysis test is shown. Next to the end banner a jetty was placed so that the user has the feeling he can easily leave the water when the test is finished. Furthermore, the image shows the high rock walls around the lake and the small beach at the end of it.

All of these details make the scene more realistic, but to further improve the realness of the scene some living creatures are missing. The first idea was to place some people in the environment, for example placing some sitting avatars at the end of the course on the jetty or animate them to go for a walk next to the river. But as an uncanny valley



(a) Street

(b) Snow on the mountains

(c) Lake at the end

Figure 4.8: Individual game objects to make the scene more natural.

effect [MMK12] wants to be avoided, it was decided to not add human-like figures, with exception of the avatar inside the pedal boat, as this animated person brings more usage than an unwell feeling. How the pedalling avatar looks like can be seen in Figure 4.9a. The uncanny valley effect describes the point when a human-like figure is too close on a human being such that people start to feel uncomfortable with it. The point of the "uncanny valley gap" is reached when the human-likeness is around 75%.

(a) Human-like Avatar (b) Birds (c) Butterflies

Figure 4.9: All animated creatures of the scene, making the scene more alive. (a) The only human-like avatar in the scene, thereby the user can see someone pedalling the boat. (b)+(c) The animated animals with their realistic look.

Another idea for a livelier environment was to place some driving cars on the street. This would have been a possibility, but the idea was discarded as the user mostly concentrate on the driving and may not see it. Therefore it was decided to add moving birds and butterflies. They are in the sky above the water and their shadows are sometimes visible on the boat. The movement, behaviour and the look of the animals seem quite real. An image of them can be seen in Figure 4.9 b and c. Counting all together there are ~800 flying animals in the scene.

4.8 Summary

As can be seen, many considerations were necessary during the implementation of the application. The first big part was to understand the functionality of the ANT+ bicycle power profile and to find out, how the messages are constructed. The table, shown in section 4.1 was very helpful for this knowledge. For the pedal boat an animated avatar was used so that the user can see the feet of the avatar pedalling in the boat. Furthermore a depth mask shader was implemented to avoid visible water in the boat, calculations were done to find the perfect speed for the movement and the display was frequently revised for a better design. All important game objects for the courses are explained and considerations to the length of the course are given. The observer has different displays for the start, during the game and when pausing the game. For these displays all settings and their usability are explained. To create a friendly environment, different game objects were used including bridges, birds, butterflies and a street. In the next section the creation of the PDF with the library "SharpPDF" was explained and details of the content were described. In the last section the used rendering effects and the anti-aliasing method is discussed and a comparison with and without the rendering effects is shown. The section further presents some visual details of the application, which are used to improve the realness of the scene.

CHAPTER 5

Results and Evaluation

In this chapter the results are given and the evaluation is described. The main part in this chapter is the user study. The detailed process of the whole test phase and one test session are described. The user study was evaluated and the results of the measurements are shown in section 5.2. Some individual participants of the user study with interesting results are discussed in detail. Furthermore, in this section the results of the Simulator Sickness Questionnaire (SSQ) [KLBL93] are shown and how they changed from pre to post questionnaire. In the next section the user feedback on different statements to the application are shown for both courses and comparisons of the courses are made. Further annotations of the participants are shown, as well as the feedback of a physiotherapist. The next section contains occurring problems, e.g. false measurements during the implementation, with some background information (i.e. why such problems can appear). As wrong values of the sensor mostly traced to the battery covers, they are explained in detail, as well as some further solutions of users. At the end of this chapter a summary is given.

5.1 User study

A user study was done to get feedback about the application and to prove if an asymmetry in the leg power is visible in a mixed group of injured, previously injured and uninjured people. At the beginning of the thesis a user study with real patients in cooperation with the FH Campus Vienna was planned. The contact person was the physiotherapist FH-Prof. Klaus Widhalm MSc. Before details and the execution of the user study were discussed, it was already clear that we would not be able to carry out the study with real patients due to COVID19. Therefore it was decided to choose just a small group of private persons to test the application. This user study was then performed with 13 participants (9 female, 4 male) between 12 and 60 ages. The mean age was 33.

Figure 5.1: The environment for the user study with the important components.

The used hardware was already mentioned in section 3.1. The stationary bike, which was a hometrainer called "Energetics - CT 350 Magnetics", was placed in the middle of the tracking area of the HTC Vive, next to the computer, which runs the application and where the observer monitors the user. As the test phase was undertaken during the summer, a ventilator was placed in front of the hometrainer. This should primarily help against the heat and should further give the user the feeling of a noticeable headwind during the ride. The sound of the application, especially the environment sound including birds, nature and the splashing water when driving the boat is an important factor to maintain the feeling of the VR environment. It was decided that the user should not use ear- or headphones in order to hear the observer of the pedal boat analysis test when he is talking to the user. One possibility would have been to play the sound on the computer screen, but the user would not feel surrounded by the sound since it would be audible that the sound comes from one direction. Therefore the computer was connected to a receiver and the sound for the test phase was played with a surround sound system. How the setup of the hardware looks like for the user study can be seen in Figure 5.1.

The duration of one test session is given with 50-60 minutes. One session contained the following points:

- the Simulator Sickness Questionnaire (SSQ) (pre and post) [KLBL93]
- an short introduction about the environment, the display and what the user has to do

- the full analysis test of the Straight Line Course
- the first part of the questionnaire
- 600 meter ride of the Buoy Course to compare the courses
- the second part of the questionnaire
- additional 2 minutes L/R balance test without the HMD

Preparations are done before the participant arrives. This means the observer already turns on the Head Mounted Display and starts "SteamVR" on the computer, as well as the analysis test application. He should place the stationary bike on the marked position in the middle of the tracking area and place the ventilator in front of it. The observer has to prove if everything is working correctly, including the sound (played with the surround sound system), the HMD and the Garmin Vector 3 pedals. He further should print the SSQ twice (for pre and post experience) and the questionnaire for the dual-sided cycling power VR game. When all these preparations are done, the participant can start the test.

At the beginning the user has to fill out the Simulator Sickness Questionnaire. It contains 16 points about the well-being of the user, e.g. general discomfort, fatigue, etc., where the user have to choose how much each symptom is affecting him at the moment by encircle one of the four options: none, slight, moderate and severe. This questionnaire is mostly done quickly and takes only 1-2 minutes.

Before the actual cycling test was done, the user got a short introduction. At first, the observer gave the most important explanation of the purpose of the application, what the user has to do and how he can steer the boat. With the help of images it was shown, how the environment and the display looks like. The whole display and functions of it were explained to the user. Further the course was described and what the user will see during the ride, e.g. two bridges, birds and butterflies. The user was told that he does not have to drive fast and that he can take his time. It was also said that collisions should be avoided but they happen often and that the user should not be upset if he collides frequently.

After the introduction it is the turn of the actual analysis test. The user takes place on the hometrainer and put on the head mounted display. He can already pedal one or two turns to wake up the sensors, as this can took up to 10 seconds. Before the observer takes place on the computer he should help the user to fix the HMD and control if the user feels save on the hometrainer. Then he starts the application in full-screen mode and fill in the names of the "patient" and the observer. The user can choose if he wants English or German as language. The other settings are the same for every user of the user study to better compare the results. As course the "Straight Line Course" was chosen, as this course gives more feedback about a possible asymmetry of the leg power. The level of difficulty was set to "Normal" for all participants. Of course this means the test may be

	Trifft nicht zu	Trifft eher nicht zu	neutral	Trifft eher zu	Trifft zu
Es fiel mir leicht, nur geradeauszufahren.	o	o	o	o	o
Ich hatte zwischendurch Probleme das Boot gerade auszurichten.	o	o	o	o	o
Die Anwendung hat Spaß gemacht.	o	o	o	o	o
Das Fahren war körperlich anstrengend.	o	o	o	o	o
Ich habe mich auf die Werte am Display konzentrieren müssen, um nicht anzufahren.	o	o	o	o	o
Die Anwendung hatte die richtige Länge (bezogen auf Fahrzeit).	o	o	o	o	o
Das Display war übersichtlich.	o	o	o	o	o
FAZIT					
Ich denke die Anwendung ist hilfreich, um Asymmetrien der rechten und linken Beinkraft zu erkennen.	o	o	o	o	o
Ich denke dass man durch häufigere Anwendung die Asymmetrie ausgleichen kann.	o	o	o	o	o

Figure 5.2: Different statements referring to the application and how the user felt during the test.

too easy for some of the users and too difficult for others. If used regularly, the difficulty level would be adapted to the user. It was further decided to not help the user through giving an offset to the weaker leg. For every participant the sound was turned on and the volume was the same. The user knew that he can start to ride the stationary bike when the information "Wait for Game to Start" disappears and the environment changes, which means all relevant game objects like the buoy chains on the sides are now visible. While driving, the user should rather remain undisturbed, but it happened that the user asked questions of interest in between, for example someone asked if it is possible to drive backwards. The observer monitors the display and the user on the hometrainer and would pause the game if the user would ask for it. Furthermore, he makes some notes about his impression of the user, e.g. if the user has problems while driving or if the user is annoyed or frustrated when he collides. When the user passes the finish line the observer helps him to take off the HMD. Then the user gets off the bike, can drink some water and sit down.

After the analysis test the first questionnaire is again the SSQ with the same 16 symptoms like before. This allows to see whether symptoms have worsened due to the VR experience. When this overall known questionnaire is done, the observer goes together with the user through the first part of the questionnaire made for this user study. But before, the user is allowed to look on the results of his measurements on the PDF report. The first questions relate to whether the user already has experience with VR glasses and if he has current or previous problems/injuries in the leg area (i.e. leg, foot or knee). If so, details are asked including the injured leg (right/left), which injury it was, if a surgery was done and if the user has the feeling the injury influenced the right/left leg balance. The next questions should give a feedback to the application and the analysis test. At first, there were some statements and the user had to answer by choosing from a scale of 1 to 5 with the options: disagree, rather disagree, neutral, rather agree and agree. The questionnaire was done in German and the statements can be seen in Figure 5.2. The user gives feedback, for example if the course was easy to drive, if he had fun and if he thinks that the application is helpful to detect and compensate asymmetries in leg power through frequently usage. Furthermore, the user was asked for suggestions to improve the application and for further annotations. During the questionnaires the user can recover from cycling the straight line course.

Since feedback on the second course was also desired, the user was asked to drive the buoy course for 600 meters, which is a third of the total distance. The process is carried out like before (for the first analysis test). The user gets introduced by the observer, who furthermore helps him to put on the HMD again. The settings are the same like for the first test, which means the sound is turned on and the difficulty level is set to "Normal", but this time the buoy course is chosen. The observer monitors the user on the computer and presses the pause menu when the user reaches a distance of 600 meters. He then exits the application premature. By doing this a PDF report will be generated and saved in the PDF-folder.

After the buoy course, the second part of the questionnaire was asked. It was clear that less specific statements could be made about this course, but it would have been too much for the user if he had to drive both courses till the end. The distance of 600 meters was enough to compare it with the other course. The user has to make some statements again with the same scale from 1 to 5. This time, just four statements were made: if the slalom was easy to drive, if the user had problems in between steering the pedal boat, if the user had fun and if it was physically demanding. Afterwards the user should compare the courses and was asked which course made more fun and which one was more difficult to drive. At the end the participant could also write down some annotations for the buoy course.

It was decided to add a short additional test at the end of a test session. In this test the user is driving again 2 more minutes on the stationary bike, but without using the application and without wearing the HMD. The observer measures the right/left balance values, the power and the cadence with a mobile app called "Wahoo" via Bluetooth. This additional test was necessary, as the right/left leg power distribution values during the analysis test are all almost ~50/50%. This is because the user always tries to get an equal distributed leg power and there can be no big deviations as the course is restricted to the right and left side. In the 2 minutes test, the user does not get a visualization of which foot is more strained and therefore, bigger deviations between the legs are possible. In future work this additional test should be integrated in the application.

This is the end of the test session for the participant. If the user wants to take home his results, the report is sent to him via e-mail. The measurements are printed and stapled together with the questionnaires and the notes from the observer, which he made during the ride. As the participants work up a sweat during the application, the foamed material from the VR glasses is washed by hand after each test to keep the glasses hygienic. Furthermore, the stationary bike is sprayed with disinfectant.

5.2 Comparison of Measurements of Test Group

In Table 5.1 all important measurements of the participants can be seen and compared. The orange marked values are the most interesting measurements. Before the measurements are discussed, it is important to look at the information of the participants regarding injuries in the leg area. The participants included two persons, which had a knee surgery within this year (participant number 9 and 13). They are 6 and 5 months postoperative after a Anterior Cruciate Ligament (ACL) tear and both are still in physiotherapy. One more person has current problems with her foot (participant number 6). She has an inflamed tendon, which means the injury is not as severe as the other two. Most of the other participants (i.e. eight persons) had earlier problems in the leg area and only two persons had no previous injuries. Two out of the eight people with earlier injuries (blue marked participants, number 2 and 4) and all three participants with current injuries have stated that they think that their problems influenced the right/left balance during the test.

The table does not contain the calculated average values of the right and left leg power, as these values are much less meaningful than originally thought. Like already shortly mentioned in the previous section 5.1 the participants always try to get a balance of ~50/50 and as the course is additionally restricted on the sides it results in a maximum deviation of 1.11%. This was reached by the participant number 4, which had definitely the most collisions (20 collisions on the left side and two on the right) and therefore an average left/right balance of 48,89/51,11%.

All participants finished the course between a duration of 14:15 minutes and 23:51 minutes. As due to COVID19 the user study was not supervised by a physical therapist or a specialist in this area, it is difficult to interpret the measurements of the analysis test and to identify if an asymmetry exists. Therefore, the conclusion in the table is more the rating of the observer than a professional diagnose of a physiotherapist. The conclusion was mainly drawn from the measurements of the collisions and the opinions and statements of the users, recorded by the observer during the test. The two minutes test was an additional help, as the results of it confirmed the observer's conclusion in each test session.

Participant	Injury	Collisions left	Collisions right	Duration	Average Power	2 minutes test (L/R)	Notes of observer	Conclusion
1	previous	1	0	14:15	135,87	54/46	pulls the participant more to the left side	slight asymmetry, left stronger
2	previous	3	1	23:51	81,20	62/38	left is much stronger	strong asymmetry, left stronger
3	none	2	0	23:09	83,66	51/49	no problems during test	no asymmetry
4	previous (2019)	20	2	21:41	93,47	53/47	left foot is stronger, very difficult for the participant	strong asymmetry, left stronger
5	previous	0	0	17:57	108,11	51/49	no problems during test	no asymmetry
6	current tendon	0	0	20:12	96,04	48/52	starts with right foot stronger, at the end no more energy in right foot	slight asymmetry, first right stronger, after a while left stronger
7	previous	3	0	19:13	102,08	52/48	drives little bit more to the left side	minimal asymmetry, left strong
8	previous	0	3	16:02	121,85	42/58	drives strongly to the right side, at the end discomfort in the left foot	strong asymmetry, right stronger
9	current (ACL)	0	8	21:16	91,16	48/52	drives strongly to the right side own feeling of driving 70/30 (L/R) to drive straight ahead	strong asymmetry, right stronger
10	previous	0	0	15:08	128,01	54/46	driving more to the left side	slight asymmetry, left stronger
11	none	1	0	19:36	98,7	52/48	drives little bit more to the left side	minimal asymmetry, left stronger
12	previous	0	0	20:04	96,47	50/50	no problems during test	no asymmetry
13	current (ACL)	4	2	15:37	125,93	52/48	drives strongly to left side own feeling of needing 10/90 (L/R) to get to the right side	strong asymmetry, left stronger

Table 5.1: Results of the measurements of the user study. The most interesting values are shown in orange colour.

5.2.1 Individual Results of Participants

Now a look is taken on some individual participants and their results (shown in Table 5.1). The biggest problems coping with the course had the participant 4. This participant had broken the metatarsal bone last year and had to wear a cast for 6 weeks. The injury actually no longer affects her, but the participant thinks that the injury is the cause of the uneven distribution. It was very difficult for her to drive straight forward and she collided 20 times with the left side. The 2 collisions on the right side were caused by too strong and rapid equalization on the left side.

The participants number 9 and 13, which are the two persons with the ACL tear surgery this year, also had some problems driving the course. They both had the feeling they had to put much more strain on the injured leg to drive straight ahead. Therefore, both of them already had slight pain on their injured foot towards the end of the course. The left/right leg power measurement of the 2 minutes test was a little bit surprising for both of them. They only had 2% more strain on the uninjured leg, but expected a larger deviation.

The third person (number 6) with current problems had also interesting results. It seems like normally her right leg is stronger, but as her injury is also on the right side, it changes after driving a while when her right foot starts to pain a little bit. The participant had no more energy in the right foot towards the end of the first course. The additional 2 minutes test also shows 2% more on the right leg due to the reason that she had a little break after the first and the second course. She thinks that a left/right balance test with no visualization and a duration of 15 minutes would show, that after a while her left foot is stronger.

Next to participant 4, also participant 2 thinks her previous injury influences the left/right leg power distribution. The injury of this participant had been a long time ago, but it was a fracture of femur that had impaired walking for years after an accident. She had problems steering the boat and was the whole test rather on the left side of the course. She had to concentrate on the right side to compensate the force. The collision on the right side happened at the beginning. The additional 2 minutes test showed the biggest deviation of all with a left/right value of 62/38%.

The last participant we want to discuss is number 8. His previous injury was a long time ago and not serious. He had big problems steering the pedal boat and was always driving strongly to the right side, although he did not expect to have any kind of problems. Towards the end, this participant's weaker foot also began to hurt. The 2 minutes test confirmed the strong asymmetry and showed a left/right balance of 42/58%. He was the only participant where a strong asymmetry was identified when no asymmetry was expected.

Results of Simulator Sickness Questionnaire

In Figure 5.3 the changes between the pre and post answers of the participants can be seen. The symptoms strength indicates the four possible answers regarding how much each symptom is affecting the user, where 0=none, 1=slight, 2=moderate and 3=severe. Only 11 of 16 symptoms are shown in the diagram, as the other 5 symptoms, which are headache, eye strain, nausea, vertigo and burping, never changed from pre to post questionnaire. The pre and post values in the diagram show the average of all participant answers. The biggest increase can be seen at "sweating" which changed from 0.08 to

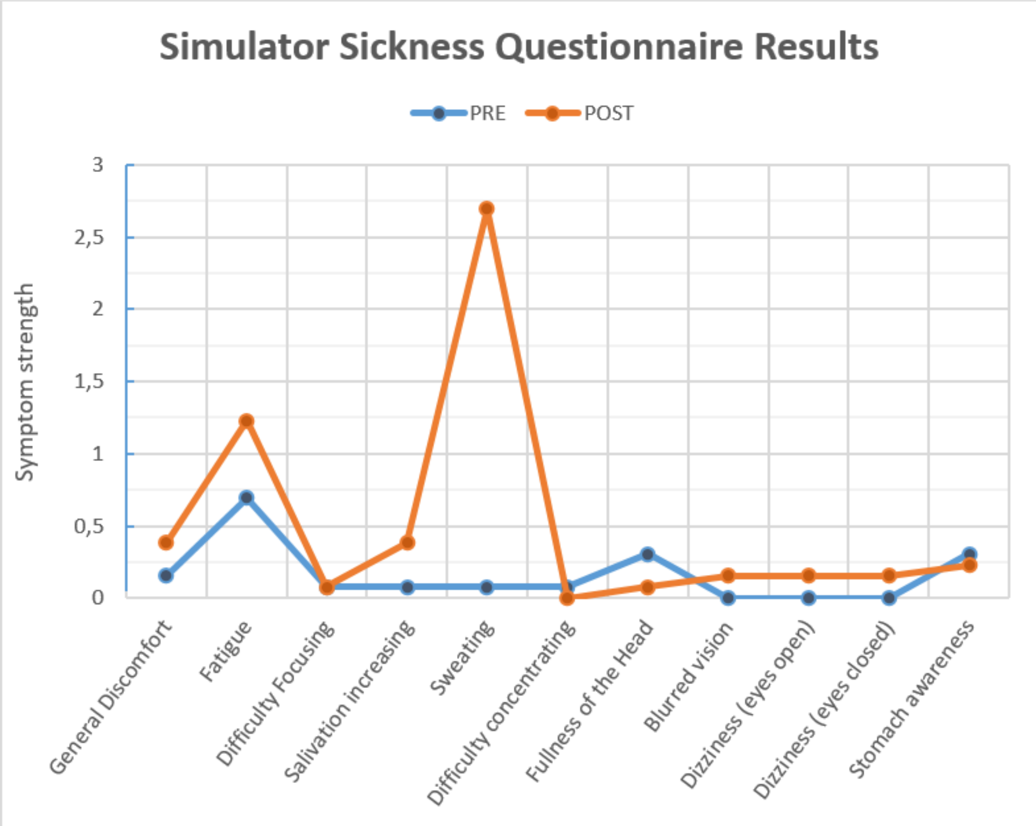


Figure 5.3: The symptoms that changed from pre to post questioning in the Simulator Sickness Questionnaire.

2.69, as every participant chose moderate or severe as strength of symptom in the post questionnaire. The second strongest increase (+0.54) had the symptom "fatigue" and the third one was the "salivation increasing" with a plus of 0.31. This shows that the biggest differences between pre and post values are affecting the symptoms which normally increase when doing sports. Furthermore, the increase of "general discomfort"(+0.23) was also due to the fact that most users were knocked out from cycling.

Some symptoms already affected the participants before they did the analysis test. This was because the most of them took the test session after work and therefore they already had symptoms like general discomfort, fullness of the head and most of all fatigue. However, it can be seen that some symptoms were getting better after the VR analysis test. This regards the symptoms: difficulty concentrating, fullness of the head and stomach awareness. The users whose symptoms improved stated that this was due to the physical activity and the friendly environment of the VR application. It helped to get a clear mind and to let go the stress from work.

Next to the five symptoms which are not shown in the diagram, the only symptom which had the same average strength in the pre and post SSQ is the difficulty focusing. This is the only one shown in Figure 5.3 because it was changed from pre to post by two participants, but one person changed it from none to slight and the other one from slight to none, therefore no changes can be seen.

The Figure 5.3 shows that next to the symptoms which are normally increase when doing sports and next to the increase of general discomfort, which was already explained, no big increase can be seen. Only the symptoms "blurred vision" and "dizziness" for eyes open and closed are getting worse after using the VR application. The average rise in all three symptoms was only 0.15 for each. Summed up, the results of the SSQ were good and the use of Virtual Reality did not or hardly affected the well-being of the users.

5.3 User Feedback

The users had to fill out a questionnaire to the application after they finished the straight line course. They had to rate all the statements, which are already shown in Figure 5.2 in section 5.1 and answer some more questions. The Figure 5.4 shows the answers of the participants, partitioned in three categories: agree/rather agree (green), neutral (red) and disagree/rather disagree (blue). The first statement represent if the participants found it easy to drive straight forward. The users had a divided opinion in this point. However, most of the users who found it easy to drive the course, had in between problems to straightening the boat. Nearby all of the participants found the application was fun (12 of 13) and also physically demanding (11 of 13), the other ones answered with "neutral".

The answers of the next statement were interesting. Some users gave the additional feedback that they concentrated on the values on the display all the time and that they could not have done the analysis test without the display. On the other hand a user said he collided just because he looked at the values on the display. The feedback showed that everyone is using the visualization of the left/right leg power distribution, but some liked the visualization on the display (with the tachometer) and some only looked on the water to see in which direction they drive.

The next question was about the length of the course. As already mentioned the length of the course was first adjusted to the length of normal cycling units in a physiotherapy session, which takes 20-30 minutes according to the physiotherapist, who was asked at the beginning of the thesis. The length was then shortened to only 14-25 minutes, as the HMD makes the user sweat a lot anyway. Although some of the user still found the length of the course a bit too long. Also the participants which took "neutral" and "rather agree" when it was asked if the course had a proper length, answered that it should maybe be a little bit shorter. No one answered that the course is too short.

After all participants fully agreed that the display was well-arranged, they had to answer the two most interesting questions. The first one was, if they think the application is helpful to detect an asymmetry in the left/right leg power, where 12 participants agreed/rather agreed and only one person rather disagreed. The one person said that

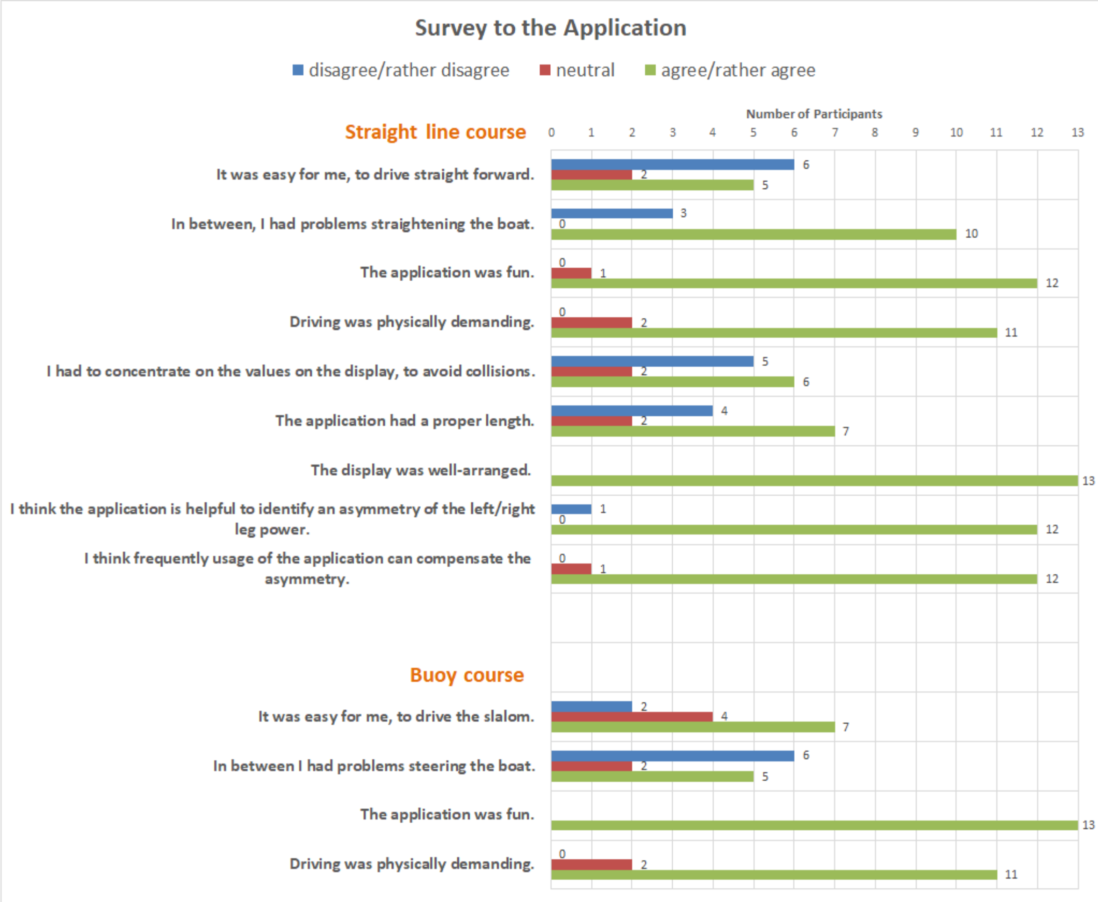
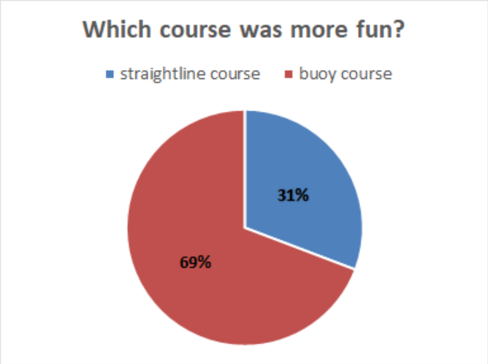


Figure 5.4: Statements to the applications and the answers from the participants.

something like the 2 minutes test have to be part of the application to recognize the asymmetry, because otherwise the people always try to get a 50/50 value. Also other people gave the feedback that a test should be included where the user cannot see in which direction he drives, but they all think an asymmetry is still recognizable, because the user notices himself, in which direction he is being drawn during the test. The second important question was if they think that an asymmetry can be improved through frequently usage of the application, where 12 users answered with agree/rather agree and the last one with neutral. The "neutral" answer was from the participant, which is also a physiotherapist. She said the application is helpful to compensate the asymmetry, but the application alone is not enough. This has nothing to do with the application itself, she accented that cycling is not enough to strengthen an injured leg. So additional to the application the user have to do some exercises to build strength.

The answers to the statements after the second course show that the second course was easier to drive. In this course no one of the users had a collision and no user drove on the wrong side of the buoy, but it has to be considered that the users drove only one



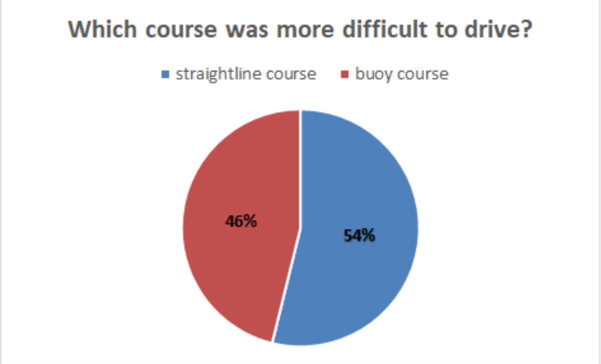


Figure 5.5: Answers of the participants in the user study when comparing the courses.

third (600m of 1800m) of the buoy course. Most of the users said, the slalom was easy to drive and only five participants had in between problems to steer the boat. All of the participants thought the course was fun and the question if the driving was physically demanding had the same results like in the first course.

In Figure 5.5 a direct comparison of the courses can be seen. The users were asked, which course was more fun, where 69% answered with "the buoy course". The opinions to the course difficulties was more balanced. 56% of the participants found that the straight line course was more difficult to drive and 46% answered with the buoy course. This shows that the buoy course was more popular, but maybe a bit too easy for the difficulty level "normal" as no user had a collision in this test.

Five out of the 13 people worn a VR Head Mounted Display for the first time and were very enthusiastic about how real everything looks. One point that was criticized by six of the 13 participants were the small pedals. When they slipped off, they could not see if they stand on it again correctly due to the VR glasses. How this problem could be fixed and other possible improvements will be discussed in more detail in section 6.1.

The users also gave some other annotations, for example two of the participants found that the HMD is uncomfortable for doing sports and another user could not see the environment always sharply. One user said it takes sometimes a bit too long till the sensor reacts to the movement, approximately 2-3 revolutions with more power on the right foot until the pedal boat is moving to the right. Other users described the steering mechanism as very realistic compared to a real pedal boat. Two participants, which both had more problems driving the analysis test would have preferred to take the test with the difficulty level "easy". The display was only criticised in one point, namely the red icon with the text "wrong direction" was deceptive. The symbol is always shown and the user thought she is driving in the wrong direction, as she did not see that below the sign is a counter which shows "0". She said that the icon has a too conspicuous colour. Not all of the comments were criticism, it was also mentioned that the environment was motivating and that the test was very pleasant and a great experience.

As already mentioned one of the participants is a trained physiotherapist. Therefore she was also asked for her opinion as a specialist. She said, she can imagine that the application is used in physiotherapy sessions, but of course it could be difficult financially, as the hardware is extensive and expensive. Furthermore, the application cannot be used directly at the beginning of physiotherapy, since patients would often be too weak on the injured leg. She emphasized the importance of visualization like in this application, as patients always need that. An undistributed balance is shown to the patients, for example, with the help of a balance board. She finds the application definitely helpful and the VR glasses would further motivate the patients, because otherwise they only see the therapy room.

5.4 Known Problems

5.4.1 Detection of Problem with Garmin Vector 3

The Garmin Vector 3 power meter was recommended by many users on different known cycling information websites (e.g. bikeboard.at [gar18], bike-components.de [Bau17], cyclist.co.uk [Stu20]). Further reasons to use this power meter for the application was the easy mount on the stationary bike and of course the possibility to measure the right/left balance. But problems of the Garmin Vector 3 were identified that delayed the completion of the application and the user study.

The pedals were not used for testing all the time during the implementation, as it would have taken too much time. Therefore, it was able to set the power and the right/left balance in Unity to steer the pedal boat without pedalling in real world. Towards the end of the implementation, the sensors were used after two weeks of implementing without the pedals and the measurements were very strange. The left/right balance was shown with 100% for left and 0% for right, although both feet were strained, and the power value was very low with ~20 Watt. The cadence was the only value which was correct. To make sure that this is not due to false calculations or errors in the application, the power meter was tested with other programs. One of them was SimulANT+, where it is possible to add a "bike power display", which shows the measured values on the computer. To exclude that the ANT+ USB stick or the ANT+ connection in general caused the problem, the values were also measured with the mobile phone app "Wahoo" via a Bluetooth connection, but this did not solve the problem either. The next step recommended by other users with the same problem was to find out what happens, if the right pedal gets disconnected in the Garmin Connect app. This leads to correct values for power and cadence, but of course the left/right balance cannot be measured without the right pedal. However, this made sure, the problem lies on the right pedal.

5.4.2 Battery Covers

The problem of dropouts of the Garmin Vector 3 is a well-known problem in the GV3 user community. According to the users, this problem is due to a poorly designed battery

(a) First design. (b) Display during Game

Figure 5.6: The 3 versions of the battery covers of the Garmin Vector 3. The first design (a) from the release of the Garmin Vector 3 in 2017, the second design (b on the left side) from June 2018 and the current design (b on the right side) from March 2020. Images from [Rid20], [Cen18] and [Kri18].

cover, as most of them had discovered power spikes, sensor outages and quickly draining batteries after the first battery change. Garmin itself confirms an issue with the battery contacts of returned Vector 3 units. Meanwhile, Garmin has developed the 3rd version of battery covers. All three versions can be seen in Figure 5.6.

In the first version, the contacts pointed inwards the battery, which resulted in short circuits. This was improved in the second version, where the contacts pointed outwards. From the first to the second design, only the battery door changed and the circuit board stayed the same. However, this only solved the problem temporarily. After some time passed with the second design, power drops and spikes occurred again for many users. Garmin found out, that the swelling of batteries under normal discharge over time causes the battery contacts to become compressed [Cen20]. This, together with vibrations due to normal cycling rides, can lead to deformation of the battery contacts, which disconnects them. In March 2020 Garmin released a new battery cover with a completely new design, which should solve the problem. It is freely available for all owners of Garmin Vector 3.

5.4.3 Solutions of Users

Before Garmin released the third version of the battery cover, many users shared their own hacks to solve the problem. There were many different approaches and the mostly

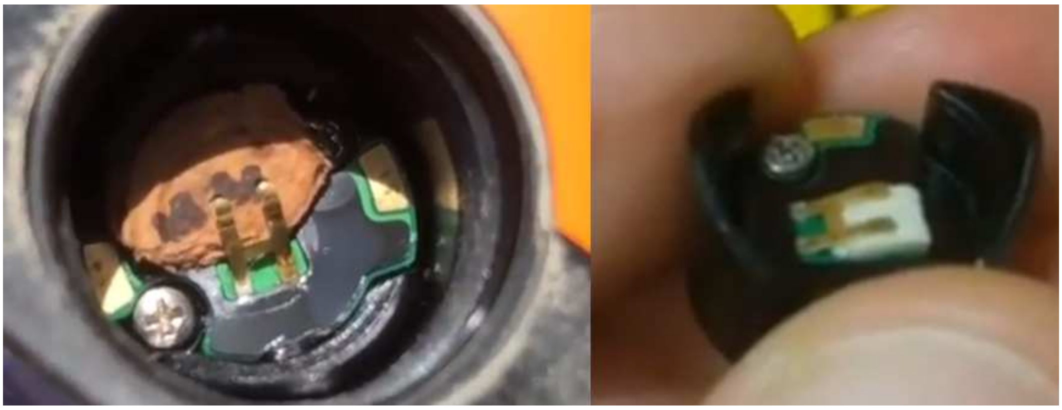


Figure 5.7: A piece of cork clamped in the spring contact to prevent the battery from losing contact.

used, which seemed to help a lot of users, are now briefly explained. The most common solution, which Garmin recommends itself in the support center, is to apply a small drop of light mineral oil on the contacts and between the batteries. Another solution recommended by Garmin is to change the battery type from LR44/SR44 where the user needs two of them for one pedal, to the type CR1/3N, where only one coin cell battery is needed for one pedal. This improves the performance as there is no risk that the contact between the batteries is disturbed. If two coin cell batteries are used, a solution, recommended by some users was to tape them together with a small strip of silicone tape. Furthermore, a solution that helped a lot of users was to put a piece of cork below the negative battery contact. How this looks like can be seen in Figure 5.7. Through putting a piece of cork below the spring of the contact, the spring is a little bit higher than before and does not lose any contact to the battery. But users have to pay attention as there are three contacts (two on the sides and one in the middle) and if the cork in the middle is too thick, the two contacts on the sides are no longer connected. Instead of a piece of cork, other users tried it with a folded aluminium foil, which leads to the same results.

5.4.4 Use of the Guarantee

The pedals for the analysis test application were firstly delivered in March 2020 and had the second battery cover design installed, although the third design was already released. The dropouts of the power meter occurred the first time after three till four months of using the GV3 in July 2020. All described solutions of users from the internet were tried to fix the dropouts. Although they helped many others users, which was visible in all the user comments, they did not solved the problem in our case. Garmin sent a new pair of battery covers of the third version, but as this also did not solve the problem the pedals have been replaced with a new pair by the company, which took over a month. When the new pair of the power meter arrived, the implementation was completed and the first three participants took the test. During the test of the fourth participant the measurements of power and the left/right balance delivered again false values. The problems were the same like the first time. Again, errors due to the application and due to the ANT+ connection were excluded. After retrying all the solutions of the users again without improvement, Garmin has agreed to send new pedals again. Despite the demand, Garmin did not provide any information about how it is possible that the pedals are broken again after exactly one week of usage. The third pair of the Garmin Vector 3 worked for the rest of the user study.

5.5 Summary

In summary, the application and especially the user study showed interesting results. The user study and especially the process of one test session is explained in detail. Afterwards a table is shown with all important results of the measurements of the user study, including a conclusion for every participant whether a bilateral asymmetry exists. The results demonstrated that the most important factor to identify an asymmetry is the own feeling of the user. After discussing some individual participants with interesting measurements, a look was taken on the results of the Simulator Sickness Questionnaire (SSQ) and how the average symptom strengths changed from pre to post survey. The users feedback to the application will be discussed in the next section and their answers to different statements are shown in a diagram. The results showed that the participants found the application was fun, physically demanding and the display was well-arranged. Furthermore, the participants think the application is helpful to identify an asymmetry in the left/right leg power and also helpful to compensate it through frequently usage. The last section in this chapter was about known problems with the Garmin Vector 3, which occurred twice during the implementation. The problems, which are dropouts, power spikes and sensor outages, delayed the execution of the user study, which was planned for July and was done in September. Often the problems are caused by the battery covers of the Garmin Vector 3, therefore the design and the different versions are described. Furthermore, some other solutions of users from the internet are given. As nothing fixed the problem in our case, the guarantee was used and new pedals were delivered by Garmin.

CHAPTER 6

Discussion

In this chapter the outcome of the research is discussed. Therefore the results of the user study are considered and compared to the aim of the work described in section 1.2. Furthermore some possible improvements for the application are discussed.

The main goal was to implement an application where the left/right leg power distribution can be measured and is returned as a visual feedback by steering the pedal boat in the VR game to the sides. Through the visualization the user can see which leg is more strained during cycling. There were already some requirements for the application defined in advance, such as the selection of 2 different courses and different levels of difficulty to best fit the users' needs. All of these requirements were fulfilled.

The user study showed, that a detection of unequal distributed leg power is possible. Although the calculated average values of the left/right balance, which are stored at the end of the analysis test in the PDF report are not significant. 12 of 13 participants had a deviation of less than 1% from the desired value of 50/50% and the last one had a deviation of 1.11%. Nevertheless, a bilateral asymmetry can be recognized through monitoring the user (on which side he is driving most of the time), by the comments of the user during the ride and the count of collisions on both sides.

The most important point is the own feeling of the user. The user himself can tell best, which foot is stronger. In the user study, every user who had problems during the test, was able to tell exactly which foot is more strained, as he can say how much he thought he strained the legs. For example, when a participant said, she has the feeling to give 70% on the left side and only 30% on the right one, but still drives more to the right side, it can be assumed that her left leg is much weaker than the right one. This is sometimes confirmed by the collisions, like in this case the user had 8 collisions on the right side.

The main use case of the application was meant for patients in their physiotherapy with injuries in the leg area (leg, knee or foot). It was not possible to execute the user study with only real patients in physiotherapy, but nevertheless, two of the participants are in physiotherapy at the moment and they both found the application very useful to see, how much their injury affected their left/right leg power distribution. One of the current injured participants is furthermore a physiotherapist herself. The feedback of an expert is important, to know, if the application is helpful and if it is suitable for usage in physiotherapy. According to the feedback, it is conceivable that such an application will be used, because the visualization makes it very advantageous for patients. Difficulties could appear with the acquisition due to the financial outlay, and for the usage of patients who are just starting physiotherapy. Depending on the severity of the injury, even the difficulty level "easy" may still be too difficult for new patients. The feedback from the physiotherapist and also from other users confirmed another goal, namely that the VR glasses have a very motivating effect, since otherwise patients only see the therapy room. Through the VR environment the patients have fun during cycling and it feels like the time passes faster.

12 of 13 participants agreed/rather agreed that they think the application is helpful to compensate a bilateral asymmetry by frequently usage and the person who answered this statement with "neutral" said it is an assistance to compensate an unequal distribution, but the application alone is not enough. Strength exercises for the weaker leg are needed to strengthen and stabilize the leg axis, which cannot be done through cycling, but through exercises like: single leg bridging, squats or lunges [Ama20]. The leg axis describes the correct alignment of ankle, knee and hip such that the strain is distributed evenly across all joint areas.

The user study has also shown that far more people are affected by a bilateral asymmetry than expected, even if it is only a slight one. Only three of the 13 participants shown no asymmetry at all. It cannot be said at which deviation from a left/right distribution of 50/50% an asymmetry exists and if a deviation of 2% can already lead to problems. Some participants had big problems during the cycling analysis test, but had only a deviation of 2% in the 2 minutes test. However, this could also be due to the fact that the additional test is too short and therefore not as meaningful as the actual analysis test. In other cases, the 2 minutes test and the analysis test showed equally strong influences, e.g. a user with three collisions on the left side, who always drove on the left side during the cycling test, got a result of 62/38 in the two minutes test, which is a high deviation of 12%. Some participants have assumed that if there is an uneven distribution of leg power, their right leg is likely to be stronger because they are right-handed. This assumption was disproved, as all of the participants were right-handed, but seven of ten users, which shown an asymmetry had a stronger left side.

Due to the count of collisions in the buoy course it can be assumed, that the difficulty level "normal" is a little bit too easy for this course. In the survey "Which course was more difficult to drive" six users chose the buoy course, but no user at all had a collision in this course or drove in the wrong direction. The participants may find the course more difficult due to the alternating strain on the left and right foot. Nevertheless, it stands to reason that the distance between the buoys is too far for this level of difficulty and therefore the course is too easy.

The Simulator Sickness Questionnaire (SSQ) did not show big changes from pre to post survey, with the exception of the symptoms which are normally increasing when doing sports. Symptoms are often strengthened by the well-known VR problem of motion sickness. Motion sickness occurs when a user is moving in the VR environment, but not moving in real world, as the brain gets the information from the eyes that the body is moving, but the body feels that he is not. An advantage of the dual-sided cycling power application is that the user is pedalling in real world, as well as in the VR game and there is no other possibility to move forward. This avoids motion sickness and furthermore the risk that symptoms like nausea or headache are increasing. The SSQ showed only very slight increases in the three symptoms: blurred vision, dizziness (eyes open) and dizziness (eyes closed). An increase from "none" to "slight" was recorded in 2 of 13 participants for all three symptoms, which is in average only a small increase.

The user study showed that the application has hardly any restrictions on the user group. The user study included both a child (12 years) and older participants (up to 60 years), as well as female and male users. It contained users with and without Virtual Reality experience. Furthermore, it included participants without injuries, with previous injuries and current injuries, as well as participants after surgery in the leg area. Both very sporty and rather unsportsmanlike participants were involved. All participants have finished the course, which shows that the application is suitable for various kinds of user groups. It is uncertain whether the application is also suitable for people who have recently been seriously injured. However, there is also the option of giving the user an offset to the weaker foot, which was not used in this user study to better compare the results. This feature increases the usability of the application for new patients in the physiotherapy. The physiotherapist would have to decide whether the application would be helpful for new patients, based on the severity of the injuries.

Since there occurred some problems with the Garmin Vector 3 power meter, another consideration would be to use other power meters for this application. The most important point would be, that the power meters are able to measure the right/left leg power distribution. Furthermore, a connection over ANT+ would be necessary to use the ANT+ bicycle device profile, as this is used in the application. A possible alternative would be the power meter "PowerTap P1". It is also pedal-based, which enables an easy mounting on the stationary bike. It sends data over Bluetooth Smart and ANT+ and can also measure the right/left balance independently. Another alternative would be the "Assioma DUO" power meter of the company "Favero Electronics". This also fulfils all requirements, which means it is also pedal-based, a measurement of the right/left balance is possible and the data transmission is done over ANT+. The price range of both alternatives is approximately the same as for the Garmin Vector 3.

For this application some more user studies could be performed to get more details. The most interesting user study would be if frequently usage can help to compensate a possibly asymmetry. Therefore, a longitudinal study would be necessary with repeated observations. Another interesting point would be if people collide more or less with the buoy chains if they would not have a display with their measurements. Some users said they only collided with the buoy chains when they focused on the display and other users reported that the display was very helpful to avoid collisions. A user gave the feedback that it was easier to drive with a higher level of resistance. It is not known yet, if another resistance level changes the results of the left/right balance.

6.1 Possible Improvements

The user study showed that all left/right balance values are close to 50/50 percent, as the participants fully concentrate on reaching an equal distributed leg power. The calculated average values are therefore not very decisive for recognizing an asymmetry. As already explained in section 5.1 all of the users did an additional two minutes test, where they drove without a HMD and without the visualization of the right/left balance. This short test is not part of the application, but should be in future work. It would be helpful if the users would do a first test, where they cannot see how much strain they put on the feet. If this test identifies an asymmetry, the straight line course of the application can be used to show the asymmetry to the user with the help of the visualization. Furthermore, this gives him the possibility to train against it. How such an additional test can be implemented in the application will be described in section 7.2 (Future Work).

The users had a positive impression of the application, but of course there were some suggestions for improvements. One point that has been criticized by most of the participants (by 6 out of 13) are the small pedals that are easy to slip off. As a pedal-based power meter is used, the pedals or the size of them cannot be changed, but a possible solution would be to attach a slipknot to the pedals, which would give the users more grip.

Furthermore, some of the users reported that the duration of the analysis test is a bit too long, but none of them would have wanted to stop the test premature, as everyone wants to reach the finish line. It would be helpful if the observer has the possibility to set the length of the course individually. Thereby, users with severe injuries, where an asymmetry can be assumed, do not have to take the full analysis test, as it is more exhausting for injured users to finish the cycling test. It would be additionally helpful to measure the pulse, as this is often interesting or sometimes also required by physiotherapists.

During the user study it was shown that it would be helpful for the observer to be able to take notes in the application while the user is driving. These notes should then be transferred to the PDF report. Currently the observer can only take notes handwritten, but a digital version would be more useful to store them and to compare them when the test is repeated. The observer should always write down how the user feels during the test or what impression he gets of the feedback of the user during the test. Every user in the user study, where an asymmetry was recognized said during the analysis test something like "I'm always driving to the right side, although I have the feeling I put much more force on the left foot". Information like this is helpful and should be wrote down by the observer.

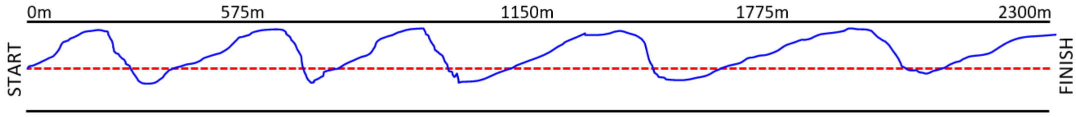


Figure 6.1: A graphic like this would show the exact way of the user, which would be helpful to recognize a right/left asymmetry.

Another improvement to better recognize an asymmetry would be a feedback in the report on which side the user was driving most of the time or a graphic of the course, which shows, where the user drove exactly. An example of how this graphic could look like can be seen in Figure 6.1. The red line indicates the middle of the course. The blue line indicates the positions of the user. In this example the user is driving most of the time near the left buoy chain and corrects strongly to the right if he is about to collide. As he always corrects the way before it comes to a collision, no collisions are shown at the end and the average values of the right and left balance would not show big differences as the user always has high values on the right side when he corrects his driving direction. In this case, the graphic would give a detailed review of the analysis test and would help to identify an asymmetry in the right and left leg power.

When patients have to drive on a stationary bike in their physical therapy, the therapist often gives a minimum watt value they should not fall below during the ride. Therefore, it would be helpful if the observer can set a minimum value in the application at the beginning of the test and the user would get a warning if his power is falling below this value. If a minimum value is given, this should further be documented in the PDF report. Another point missing in the report is the offset the observer can add to the patient. It should be also recorded in the document, as it may be important to know if an offset was added when the test is repeated.

In the PDF report can be seen on which side (right or left) the collisions took place. This often gives an additional feedback to the right/left balance of the user, for example if the user has 5 collisions on the right side and no one on the left, it can be assumed that his right foot will be more strained when driving. A point that is missing in the report is the information at which distance the collisions took part. For example, if a user had 2 collisions, but both happened within the first 50 meters when the test was started and he does not have any problems afterwards, it can be assumed that the collisions happened only because the user learned how the steering mechanism works. Therefore, in this situation the collisions would not be very informative regarding the right/left balance.

Some improvements were mentioned, which should serve to increase the motivation. Especially after the second bridge in the application, some users had the feeling that it took forever to reach the finish line. Motivational factors would be to place some cheerleader or a cheering crowd on the sides in the last 300 meter of the course. This concept is also used in various sport games, e.g. in Wii Sports. Another motivational factor for the users would be to get information like "200 meters left". Of course the user can also read out this information in his display, but he does not pay as much attention to it as he would, if he receives the information in a large flashing text. Furthermore, the possibility to turn on real music would be motivating.

The participants were very open and creative when they suggested improvements for the application. Therefore, there were also improvements mentioned like "splashing water in real world during the test", "driving at night" and "the possibility to choose an existing environment, e.g. driving through Prague". To make the feeling of driving a pedal boat more realistic, it was recommended to use a recumbent bike as stationary bike. Furthermore, participants mentioned it would be nice to have more moving objects (e.g. humans, dogs, cars) in the scene and that the butterfly should fly to the pedal boat when the observer presses a button.

CHAPTER 7

Conclusion and Future Work

7.1 Conclusion

In this diploma thesis a Virtual Reality application was implemented, which should help to identify if the user has an unevenly distributed leg power in the left and right leg during cycling on a stationary bike. A pedal-based power meter (the Garmin Vector 3) was used as sensor to measure the right/left leg power distribution and to visualize it in a serious VR game. This is done by steering a pedal boat to those side, on which the user puts more strain on the foot. The application consists of two different courses and three difficulty levels. In the first course, the user has do drive straight forward and should try to not collide with the buoy chains, which restrict the course on the left and right side. In the second course the user has to drive a slalom, which means he has to alternate the strain on the feet.

The application should be used during physiotherapy. A user study with real patients, which are currently in physiotherapy by reason of leg, knee or foot injuries or because of a surgery in one of these areas, was not feasible due to the restrictions of COVID 19. Nevertheless, a user study with 13 participants between 12 and 60 years was carried out. One test session contained a Simulator Sickness Questionnaire (SSQ) (pre and post survey), a questionnaire to the application, the full cycling analysis test of the straight line course, driving 600 meters of the second course i.e. the buoy course and an additional 2 minutes test to measure the left/right balance without the application such that the user cannot see in which direction he is driving. The performed user study included two participants, who are currently in physiotherapy due to an Anterior Cruciate Ligament (ACL) tear that was operated this year in both cases, one participant with a current tendinitis and most of the other participants (8 of 10) had previous injuries in the leg area.

The results of the user study showed that it is possible to recognize an asymmetry in the leg power. It turned out, that the average calculation of the right and left leg power is not that meaningful, as the user focuses on achieving an even distributed strain during the test. Therefore, an unequal distribution was identified through information of their collisions, the monitoring, where the observer can see on which side they drive most of the time and the user's individual feedback. The conclusions, whether an asymmetry exists is based on the observer's rating and not diagnosed by a physiotherapist. It has been shown that five out of 13 participants have a strong asymmetry. Of these five people, two had a surgery on their knee this year, one person had an injury on her foot last year, one person had very serious injuries a long time ago, which affected her gait for several years and the last person was uninjured. In contrast to the injured and previous injured participants, the uninjured user assumed that no asymmetry will be discovered. The participant with the previous severe injury was also surprised, because she did not expect that this would affect her leg power distribution that much. The application has shown that uninjured people and previously injured people can also be affected by an uneven distribution of the leg power.

Furthermore, one of the participants is a physiotherapist and rates the application as very helpful to recognize asymmetries and to visualize the user, how he strains his feet, as patients always need this visualization to understand how the injury affects their leg power distribution. The physiotherapist also thinks the application is helpful to compensate an unequal distribution of the left/right leg power through frequent usage, but further strength exercises are required to stabilize and strengthen the leg axis. Furthermore, she gave the feedback that she can imagine to use the application in her therapy sessions.

The Simulator Sickness Questionnaire did not show big differences in the survey before and after the analysis test. The most increasing symptoms were sweating, fatigue and salivation increasing, which are all normally increase when doing sports. Attributed to the VR game can be the slight increases in the symptoms: blurred vision and dizziness (eyes open and closed). The questionnaire for the application showed that most of the users had more fun when driving the buoy course (69%) and about half of the users found the straight line course was more difficult to drive (54%). Nearby all of the participants think the application is helpful to identify an asymmetry in the left/right leg power and that it is possible to compensate it through frequently usage.

7.2 Future Work

The user study revealed opportunities for improvement in various areas, both for the observer and for the user. In future work the possible improvements, described in section 6.1 should be implemented. Of course not all mentioned suggestions of the participants are significant and realizable, but some of them would be easy to implement and would improve the benefit of the application. Especially helpful would be additional informations in the PDF report, like the distances, where the collisions happened and the notes of the observer he wrote down during the test. To identify an unequally distribution of the leg power, a graphic (like in Figure 6.1) with the exact positions of the pedal boat would be important.

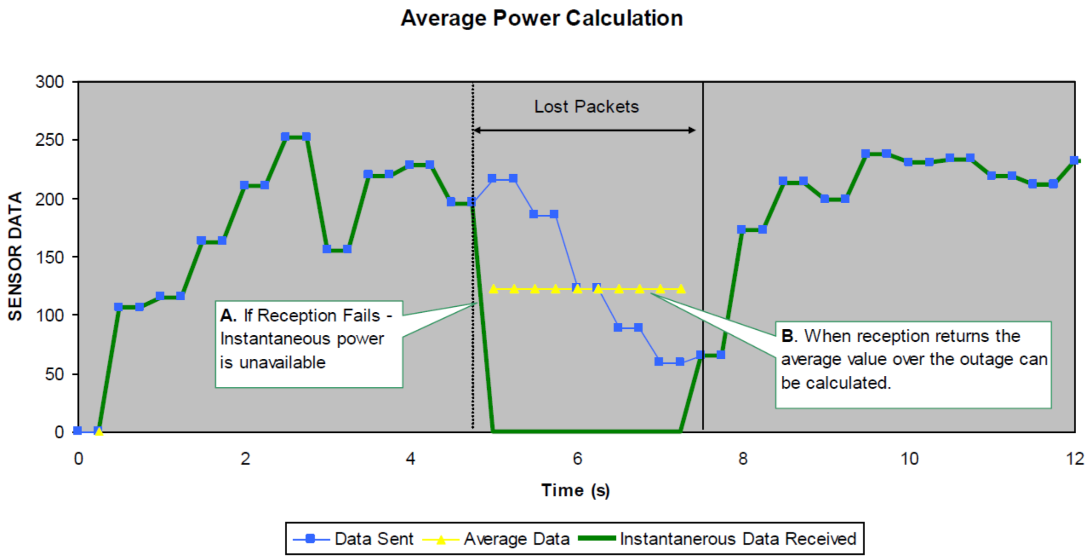


Figure 7.1: Averaging power during RF reception loss. Image from [Inc19].

As also mentioned in the possible improvements, something like the additional 2 minutes test should be part of the application. This test should be done at the beginning so that the physiotherapist can see the left/right balance values, without the user knowing what is measured exactly. The test should have a duration of a normal ergometry, which takes 20-30 minutes. A possibility to integrate such a test in the application would be to add a course, which looks like the straight line course, but here the left/right balance of the user does not influence the driving. Another option would be that the user can see when he is pedalling to the left or right side, but the strength to drive to one side is set much weaker, so that the user only drives slightly to the left with a value of 55/45% and not already with 51/49%. If no good way can be found to include such a test into the application, it would still be important that the physiotherapist will be informed to carry out such a test beforehand. For example, the patient can drive a normal ergometry the first time, in which the left/right leg power distribution is also measured and in the second physiotherapy session the user can start to drive the straight line course from the application, where the values are visualized.

A consideration for future work would be to replace the power meters with other pedal-based power meters, as there occurred some problems which could only be fixed by replacing the Garmin Vector 3 with new ones. Two alternatives, which fulfil all requirements would be the "ASSIMO DUO" and the "Powertap P1". To make such a decision, further information about the sensors have to be gathered and customer reviews need to be read.

Another important point is the problem of lost packets during the analysis test. It was rare that the pedals dropped out, but it could become a problem if the data transfer is not working well. If packets are lost, the instantaneous data received will be set to zero.

This affects the power and the cadence in this application, as the instantaneous values are used. A possibility would be to request if the instantaneous power is available and if it is not, an average value over the outage can be calculated and used as power during the reception loss. How this looks like can be seen in Figure 7.1.

The last point for future work is to pay more attention on the performance. The application runs smoothly, but the application can still be optimized. Individual models can be simplified, such as the pedal boat, which is a high polygon model.

With all these improvements, the application would improve in quality. Many of the described suggestions for future work would help a physiotherapist to diagnose an uneven left/right leg power distribution. The other points should improve the application in overall. The application is already helpful to visualize the user whether there is an asymmetry in his leg power.

List of Figures

List of Tables

Acronyms

ACL Anterior Cruciate Ligament. 19, 20, 56, 58, 73, 77

ACLR Anterior Cruciate Ligament reconstruction. 19

ANT Adaptive Network Topology. 3, 4, 14, 21, 22, 25–27, 31, 33, 48, 63, 66, 69

AR Augmented Reality. 7, 8, 77

CTS Complete Terrain Shader. 29–31, 42, 46, 77

GV3 Garmin Vector 3. 12, 14, 24, 25, 63, 65, 77

GV3s Garmin Vector 3s. 14

HMD Head Mounted Display. ix, xi, 9, 27, 42, 53–55, 60, 62, 70

HTC High Tech Computer Corporation. 7, 9, 17, 24, 27, 52

Hz Hertz. 25–27

PBR Physically Based Rendering. 30

PCO Platform Center Offset. 14, 27

PD Parkinson's Disease. 18

PDF Portable Document Format. 3, 26, 28, 30, 33, 40, 43–45, 48, 54, 55, 67, 70, 71, 74, 78

PP Power Phase. 14

RF Radio Frequency. 26, 75, 78

SSQ Simulator Sickness Questionnaire. 51–54, 60, 66, 69, 73, 74

TAA Temporal Anti-Aliasing. 45

TPI Threads Per Inch. 23

VR Virtual Reality. ix, xi, xiii, 1–3, 5, 7–9, 15–21, 24, 26–28, 31, 42, 43, 52–56, 59, 60, 62, 63, 67–69, 73, 74, 77, 78

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