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Development of a motor speed control concept to a cross-country sit-ski for rehabilitation purposes

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Abstract

This thesis explores, builds and tests two motor speed control systems for a belt-driven cross-country sit-ski with an electric motor. The purpose of this is to use it in rehabilitation of individuals with leg impairments. Rehabilitation of individuals with leg impairments commonly uses submaximal HR exercise. However, since cross-country sit-skiing is an exhausting sport that requires specialized slopes to be executed, it is not possible to use it for rehabilitation purposes.

To address this, two concepts was developed using the heart rate (HR) to control the motor speed. The following concepts was: (1) a PPG motor control concept and (2) an ECG motor control concept. These were tested in snow conditions and on asphalt. The results showed that the PPG sensor gave inaccurate HR measurements, while the ECG was more accurate. This means that the ECG concept can be used for rehabilitation purposes.

Future research should get user feedback and commercialize the product to make it accessible for users. The motor speed control concept will need further testing and calibrating. It will be important to get qualitative feedback from the potentially relevant user group, which is individuals with leg impairments.

Sammendrag

Denne oppgaven utforsker, bygger og tester to motorhastighetskontrollsystemer for en beltedrevet piggekjelke til langrenn med elektrisk motor. Formålet med dette er å bruke det i rehabilitering av personer med funksjonsnedsettelse i nedre halvdel av kroppen. Under rehabilitering av personer med slik funksjonsnedsettelse brukes vanligvis submaksimal trening, men siden piggekjelking er en utmattende sport som krever spesialtilpassede løyper for å bli utført, er det ikke mulig å bruke sporten til rehabiliteringsformål i dag.

For å kunne bruke konseptet til rehabilitering, ble hjerterytmen brukt til å styre motoren. De to følgende konseptene for motorhastighetskontroll ble utviklet: (1) et PPG-motorkontrollkonsept og (2) et ECG-motorkontrollkonsept. Konseptene ble testet i snøforhold og på asfalt. Resultatene viste at PPG-sensoren ga unøyaktige hjerterytmemålinger, mens ECG var mer nøyaktig. Dette betyr at ECG-konseptet kan brukes til rehabiliteringsformål.

Fremtidig forskning bør få tilbakemeldinger fra brukere og kommersialisere produktet for å gjøre det tilgjengelig for brukere. ECG-konseptet for motorhastighetskontroll vil trenge ytterligere testing og kalibrering. Det vil være viktig å få kvalitative tilbakemeldinger fra den potensielt aktuelle brukergruppen, som er personer med nedsatt funksjonsevne i nedre halvdel av kroppen.

Preface and Acknowledgements

This master's thesis is a collaboration between the Department of Structural Engineering and the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology. The work is a continuation of Aase and Forr's master's thesis from last year.

I want to thank my supervisors Arild Holm Clausen and Knut Einar Aasland for giving me the opportunity to write a different master's thesis than what is standard practice at the department. Thanks to my co-supervisor, Sindre Wold Eikevåg, for his great presence and encouragement throughout the thesis. Big thanks to Bjørn Åge Berntsen for his priceless help and enthusiasm. I would also like to thank Martin Steinert for his invaluable advice. Thanks to Håvard Vestad for sharing his knowledge and support. Thanks to all the master's students who have helped me at the lab, especially Martin Francis Berg, Ole Nesheim and Håkon Bentengen. Thanks to Ole Tobias Utne Bjerke for taking time to help me with testing. Lastly, I have to thank the PhD-candidates at the lab that had my back in times of need: Marius Auflem, Kjetil Baglo and Kim Christensen.

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Acronyms

BPM Beats per minute. xi, xii, 18, 22–26, 38, 40–43

ECG Electrocardiogram. iii, v, ix, xi–xiii, 6, 33–43, 45, 47–49

GRD Ground. 9, 12

HR Heart rate. iii, ix, 5, 7, 8, 12, 17, 18, 22–24, 26, 31, 33, 36, 41, 42, 45, 48, 49

PPG Photoplethysmography. iii, v, ix, xi, xiii, 6, 7, 12–14, 17, 19–23, 25–27, 29, 31, 33, 40, 47–49

Chapter 1

Introduction

While many are familiar with cross-country skiing, few have heard of cross-country sit-skiing. The sport involves athletes with impairments in their lower body sitting on a sledge mounted on two skis performing a double poling technique to create propulsion [1]. Cross-country sit-skiing is a Winter Paralympic sport, but can also be enjoyed for recreational purposes [2]. Creating propulsion using only the upper body is challenging and therefore the competition trails are accustomed to this. However, the Norwegian lighttrails does not take this into account. Zimmermann describes it as follows in her project thesis: "The cross-country trails in Norway are steep and curved, making them inaccessible to cross-country sit-skiers. [...] It is harder to generate force using only the upper body. Inevitably, uphill poling is challenging. Downhill slopes can also cause difficulties. If the slope is curvy, steep, or long, the sit-skier can lose control and fall" [3]. The activity is therefore limited to certain slopes and does not provide the sense of freedom many associate with cross-country skiing. To face these challenges, the equipment has to be improved.

1.1 Cross country sit-skiing - the sport

Cross-country sit-skiing is one of the three major sport classes in cross-country skiing at the Winter Paralympics. Since sit-skiing is a strenuous sport, the tracks are specifically designed to accommodate sit-skiers. The sit-skiers are also divided into different classes. Zimmermann describes it in this way: "The World Para Homologation Guide specifies that these courses cannot have any steep hills, with a gradient $> 12\%$, that they should have straight run-outs after a downhill slope, and that corners should be placed where speed is slow [4]. In a 3 km course, the maximum climb is 15 meters for sit-skiers, compared to 65 m for regular cross-country athletes [5]. Further, to ensure fair competition, the sit-skiers are classified into five categories based on their trunk control: LW10, LW10.5, LW11, LW11.5, LW12 [6]. The ability to extend and flex the trunk determines how large momentum is transferred to the poles and therefore has a large impact on the propulsion generation [7]. Class LW10-athletes have limited trunk muscle control to the point where they would not be able sit [up straight] without support of the upper body. Class LW12-athletes, on the other hand, have normal trunk control" [3]. The most common sitting positions are (1) with legs stretched out or (2) with the knees under the hips. The second of the two are usual among users with greater trunk control [8].

(a) Spike Snow **(b)** HandiSnow 5 **(c)** Beitoskilator

Figure 1.1: Various sit-skis on the marked

The equipment on the marked today is a variety of sit-skis with different sizes, weights and sitting positions. Exero Technologies offers a light-weight sit-ski called Spike Snow with the first sitting position, as shown in figure 1.1a. HandiSnow 5, see figure 1.1b is another option with the second sitting position and a handbrake [9]. Another option is the BeitoSkilator shown in figure 1.1c. The sit-ski has a swivel seat which is supposed to make it easier to get in and out and it has four skis instead of two which introduces the opportunity to turn using the body to move the mass centre [10]. Something all the sit-skis has in common is that none of them provide any propulsion assistance. This is something the previous master's thesis wanted to improve.

1.2 Previous master's thesis

This thesis is a continuation of Aase and Forr's master's thesis. Their work is explained as follows in Zimmermann's project thesis: "In order to improve the assistive technology available for sit-skiers today, Aase and Forr built a propulsion assisted prototype of a cross country sit-ski, see figure 1.2. The drive system consists of a belt with an electrical bicycle hub-motor powered by a bicycle battery provided by Elsykkelbutikken [11]. The motor is activated by a throttle attached to the ski poles, which is connected to the motor by a wire. Linear actuators are used to move the belt up and down, and braking can be performed using the mechanical brake between the legs. With this prototype, the users were suddenly able to conquer a steep alpine slope with a gradient of 23%. These results are remarkable when comparing it to the maximum gradient of 12% in Paralympic courses [4]. The testing also found that the belt had resistance and worked as a downhill brake" [3].

Figure 1.2: Previous prototype developed by Aase and Forr

The motor system is taken from an electric bike. The motor, see figure 1.3, is a Bafang 36V 250W geared rear hub DC motor [12] and the battery consists of a Shanshan Hailong Battery case with 52 Samsung-29E 18650 rechargeable lithium battery cells [11]. In addition, there is a control unit extended by a display, a power button and a thumb throttle.

Figure 1.3: The motor is a Bafang RM G040.250.D

Aase and Forr used the thumb throttle to control the motor speed. The throttle was attached to one of the poles and user could adjust the wanted motor help by pushing the throttle with the thumb. This proved to be an inconvenient solution. Users reported that the motor had an abrupt start with the throttle and that the placement was too high, making it hard to adjust the speed of the motor [11]. Some users had to stop poling and adjust the throttle, which disrupted the rhythm of the sit-skiing. Additionally, some users pointed out that fine movements of the hands, such as pushing a button, can be hard to do due to hand spasms [3]. The experience could become more pleasant if the motor speed control is improved.

1.3 Relevant academic literature on rehabilitation

Sit-skiers have impaired leg function [13]. The reason is different from individual to individual. It could be due injuries, impairments or disabilities such as spinal cord injury, stroke, amputations, cerebral palsy (CP) or spina bifida [14][2][15]. Many of these individuals are in need of rehabilitation. Rehabilitation is the term used to describe restoration of physical function after injury or dysfunction [16]. An example is stroke survivors. The time after a stroke requires rehabilitation. Low- to moderate-intensity aerobic activity is recommended as training in rehabilitation for stroke survivors [17].

In individuals with spinal cord injury, cardiovascular function often decreases, causing negative consequences on physical and psychological aspects of their lives [18]. Hoffman [19] states: "Ordinary daily activities of those with spinal cord injury are usually not adequate to maintain cardiovascular fitness, and lack of participation in a regular activity programme may result in a debilitative cycle". The consequences of this can be reduced physical independence and increased risk of cardiovascular disease [19]. During rehabilitation of cardiovascular disease, submaximal exercise training is used in order to facilitate for subtle changes in physical activity in an inactive group of individuals [20].

Submaximal exercise should not exceed 85% of the maximum HR, and include exercise such as arm ergometer or upper body poling. A study comparing exercise efficiency between arm ergometer and upper body poling showed a similar response in the cardiovascular system, implying that the two training methods are similar [21]. In a sports rehabilitation program for cerebral palsied individuals, the submaximal HR of individuals conducting a 12-month arm ergometer program were significantly lower than in the beginning [22]. This shows that submaximal training can have the same effect on individuals with CP as with able-bodied individuals, and that it is logical to assume that upper body poling will have similar effect on the cardiovascular system as arm ergometer exercise. This implies that upper body poling can be used in rehabilitation focusing on submaximal exercise.

1.4 Problem description and objectives

As described in section 1.1, there are multiple cross-country sit-skis available on the marked. However, there are no sit-skis with propulsion assistance. Therefore, there are few solutions on how to control the motor speed. The thumb throttle solution described in section 1.2 proved to be insufficient on multiple levels. Hence, the problem description of this thesis is to investigate and find a solution on how to control the motor of the sit-ski. An aim in the development is to make the motor experience feel natural to the user. As the thesis progressed, it moved into a new direction. What if it is possible to use the sit-ski as a tool in rehabilitation by using the HR to control the motor? The prospect of this was investigated.

Thesis objectives:

- Explore the possibilities of sit-ski motor speed control
- Build and test a motor speed control concept
- Investigate the possibility of using the solution for rehabilitation purposes

1.5 Thesis structure

Due to the progressive nature of this master's thesis, it does not rigorously follow an IMRaD structure. Rather, it follows the development process. However, the two tests that is presented in section 3.3 and section 4.2 follows the well-known structure of method, results and discussion and conclusion.

The introduction presents the sport of sit-skiing, the previous master's thesis and relevant academic literature on rehabilitation. Significant parts of the project thesis was included, but the complete project thesis can be found in Appendix B. Other than the theory presented in the chapter 1, supplementary theory will be included throughout the chapters. Examples of such theory can be theory about the development process or the different sensors. The purpose of this is to get a better flow in the thesis.

Chapter 2 describes the ideation phase of the process. This was a diverging phase where multiple ideas were created. Three ideas were explored deeper in section 2.3, 2.4 and 2.5. Further, chapter 3 covers the development of a motor control system using a PPG sensor. As the system did not show the wanted results, a new system with an ECG sensor was built and tested in chapter 4. Lastly, the final discussion, conclusion and further work are represented in chapter 5 and 6, respectively.

Chapter 2

Ideation phase

Brown [23] describes the ideation phase of a design project as "the process of generating, developing, and testing ideas that may lead to solutions" . It is a diverging and exploring phase that requires creative thinking. When diverging, choices are created [24]. How this was done is described in section 2.1. After diverging, it is time to converge. Converging is the act of making choices [24]. Three ideas was explored further to prevent the unfortunate form of design fixation where the designer makes a commitment to one design solution prematurely [25].

2.1 Diverging - coming up with multiple ideas

Diverging is about coming up with multiple ideas and this is important to avoid design fixation. By exploring multiple ideas it is likely to avoid getting married to one idea. Table 2.1 represents the different ideas on how to control the motor.

Some of the ideas were more realistic to execute than other ideas. The technology has to be available to realize the idea, so ideas such as the eye-tracking idea is not realistic to proceed with. Three ideas were explored further: motor control by (1) load cell in pole, (2) HR data from PPG sensor and (3) accelerometer attached to the sit-ski. But before the ideas could be examined, the motor had to be accessed.

Table 2.1: Ideas on how to control the motor during the ideation phase.

Idea	**Description**
EMG sensor	Connect EMG sensor to bicep to measure the contraction of the muscle. Adjust the motor help depending on muscle size and frequency.
Weight distribution	Using the change in the distribution of the weight during poling to give motor help, similar to a Segway.
Pole position	Tracking the pole position to assess where in the poling motion the user is and giving motor help according to this.
Heart rate	Adjusting the help from the motor from the HR of the user. For example giving more help when the pulse is higher.
Inclination of belt	Measure the inclination of the belt to assess whether the user is poling uphill, downhill or flat. The amount of help can be adjusted to how the inclination.
Force sensor in seat	Using a force sensor in the seat to track the poling forces and give motor help when the user is poling.
Axial force sensor in pole	Measure the axial force in the pole to track the poling motion and give motor help accordingly.
Voice activation	Using voice to activate and adjust the speed of the motor.
Head angle	Measure the angle of the head by attaching a sensor to the hat.
Pedal under arm	Attach a pedal under the arm that is compressed when the user is poling.
Movement sensor	Attach a sensor to the side of the ribcage that tracks the movement of the arm. Can adjust the motor help depending on the frequency of the poling.
Eye tracking	Using eye tracking to adjust the speed of the motor. For example getting more help when looking further ahead and less when looking down.
Hand throttle	Switch the placement and size of the hand throttle to make it feel natural for the user.
Heat measurement	Measure the heat of the user and adjust the motor help according to temperature.
Deformation	Measure the deformation of the sit-ski while poling forces act on it and use it to adjust motor help.
Accelerometer	Use an accelerometer to get the acceleration data of the sit-ski and adjust the motor speed after this.

2.2 Accessing the motor

Before the motor control ideas could be tested, the motor had to be accessed. In this case, accessing the motor means to be able to send information to the motor in the form of a signal that adjusts the speed. The motor system consists of the following parts: the rear motor (1), controller (2), monitoring screen (3), on/off button (4), battery (5) and thumb throttle (6). The motor it connected to the controller by a 9 pin motor connector. The controller is further connected to the battery and an 8 pin 1T4 cable. The 8 pin 1T4 cable splits into four cables and connects to the the monitoring screen, on/off-button and thumb throttle. There are multiple ways to access the motor. This can be done by

1. **Accessing through the 9 pin motor connector**. This can be done by cutting the cable that gives power to the motor. The main motor connector is an overmolded HiGo Z910 with three power leads, five Hall sensor wires and one signal wire. To access the motor through this connector, all the different signals to each pin have to be mapped out and replicated.
2. **Accessing through the controller**. The controller sends signals from the 8 pin 1T4 cable to the 9 pin motor cable and regulates the power from the battery. The connector in this system was moulded in silicone. This was most likely done to keep the system waterproof. Therefore, to access the controller the silicone mold had to be carved out. Afterwards, the controller could be studied to find out what signal controls the motor speed.
3. **Accessing through the thumb throttle**. The thumb throttle sends a signal to the controller that directly influences the speed of the motor. Which signal the throttle sends out has to be established and replicated.

The easiest way to access the motor proved to be through the thumb throttle. The reason for this is because the thumb throttle sends one signal, which compared to the seven signals of the 9 pin connector is easier to replicate. The controller is also a more complicated system with multiple signals. It already regulates the power from the battery, so it is safer to keep it as it is. Also, it can be an advantage to keep the controller waterproof.

The thumb throttle is a Hall sensor throttle of the type Honeywell Linear Hall-effect Sensor ICs SS39ET/SS49E/SS59ET Series [26]. To understand the throttle, the principle of reverse engineering was used. Reverse engineering is a top-down process that assesses and analyses the original parts for the purpose of reinvention [27]. After disassembling the throttle and reading the data sheet, it proved to have three cables; one for input voltage, one for ground (GRD) and one for an analog signal. It is this analog signal that controls the motor speed, and therefore it has to be replicated. Using an Arduino Uno, the throttle was given an input voltage of 5V. The analog signal was read using the built-in command AnalogRead() in the code. This command maps the input voltage from the throttle into integer values between 0-1024 [28]. The throttle had a minimum value of 173 and a maximum value of 881. The calculation of the minimum and maximum value in voltage can be seen in equation 2.1 and 2.2, respectively. This is the voltage signal that has to be replicated to control the motor speed.

$$V_{min} = 173 \times \frac{5V}{1024} = 0.85V \tag{2.1}$$

$$V_{max} = 881 \times \frac{5V}{1024} = 4.31V \tag{2.2}$$

Next, a way to send the same signal back to the motor had to be found. An Arduino is capable of sending a digital signal of 0 or 1. Pulse-width modulation was used to turn the digital signal into an analog one. The principle of pulse-width modulation is that switching a digital signal on and off for different time periods can simulate an analog signal [29]. In the Arduino code, this command is called AnalogWrite(). A linear potmeter was used to test the signal output. The setup can be seen in figure 2.1. The figure shows how the Arduino is connected to the potmeter and sends a signal to the motor through the thumb throttle cable (white and blue cable to the right). The code can be found in Appendix A, section A.0.1. This is the way the motor was accessed.

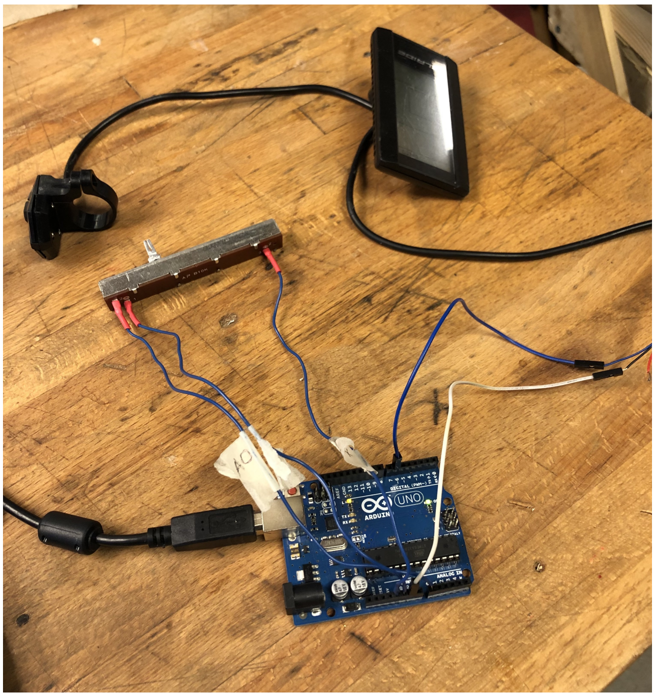


Figure 2.1: Setup of the potmeter controlling the motor speed.

2.3 First idea - motor speed control by load cell in pole

The first idea that was explored further was the one with a load cell in the pole. The reason why the load cell was an interesting concept to look into was because the force and frequency of the poling motion could easily be tracked. Therefore, the motor speed could be matched directly to the poling motion, which could make the experience feel natural and pleasant for the user.

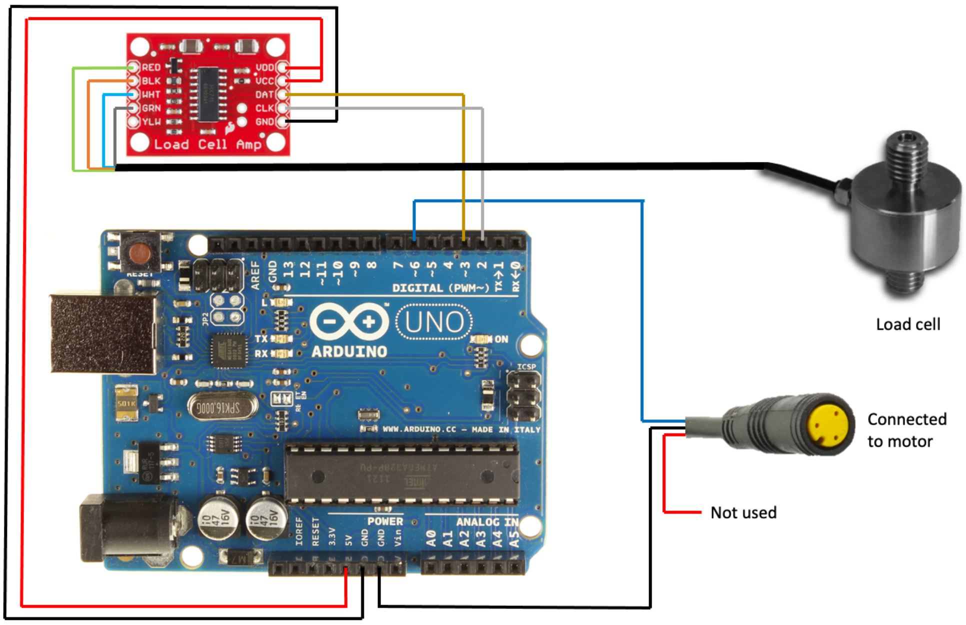
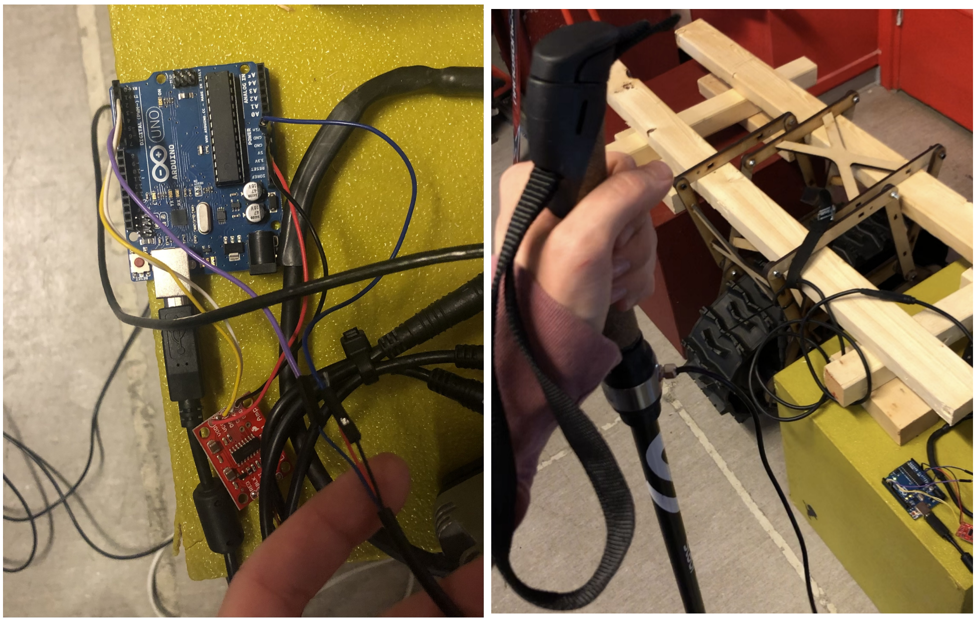


Figure 2.2: Wiring diagram of motor system with load cell.

The system is made of an Arduino Uno microcontroller, a load cell and an amplifier. The amplifier enlarges the signal from the load cell and makes it easier to read for the Arduino. The load cell is a 200 series in-line 2kN load cell [30] and the amplifier is a Sparkfun breakout [31] that is modified to have an 80 Hz sampling rate. The load cell is soldered to the amplifier according to the instructions in the datasheet. The load cell was calibrated using the code in Appendix A, section A.0.7. The final setup for the wire connections can be seen in figure 2.2. To fit the load cell inside the pole, a part of the pole was cut out. Two modules was additive manufactured to incorporate the load cell into the pole by glue. The load cell in the pole can be seen in figure 2.3b.

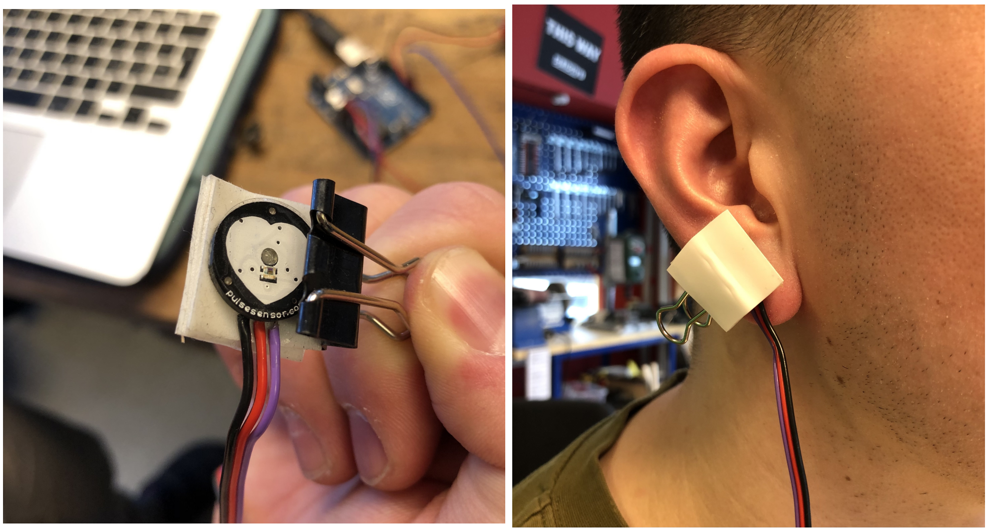


(a) Arduino setup. **(b)** Load cell and motor.

Figure 2.3: Setup of motor control by load cell.

2.4 Second idea - motor speed control by HR data from PPG sensor

The second idea was the idea of controlling the motor using HR data from a PPG sensor. A PPG (photoplethysmography) sensor registers the light absorption of the capillaries and determines the HR [32]. Normally the sensor is placed on the earlobe or the finger tip due to the high concentration of capillaries and low amount of tissue. It was a natural choice to attach the sensor to the earlobe as the fingers would be in constant movement while poling. The sensor was taped to a clip to be attached to the earlobe, as seen in figure 2.4. The PPG sensor [33] used in this project is compatible with Arduino and has three wires; supply voltage, GRD and pulse signal. The wiring diagram is shown in figure 2.5. As the test subject started moving and his pulse raised, the motor started going faster. The code can be found in Appendix A, section A.0.3. The whole setup is shown in figure 2.6.



(a) Ear clip.

(b) Ear clip attached to earlobe.

Figure 2.4: Ear clip with PPG sensor.

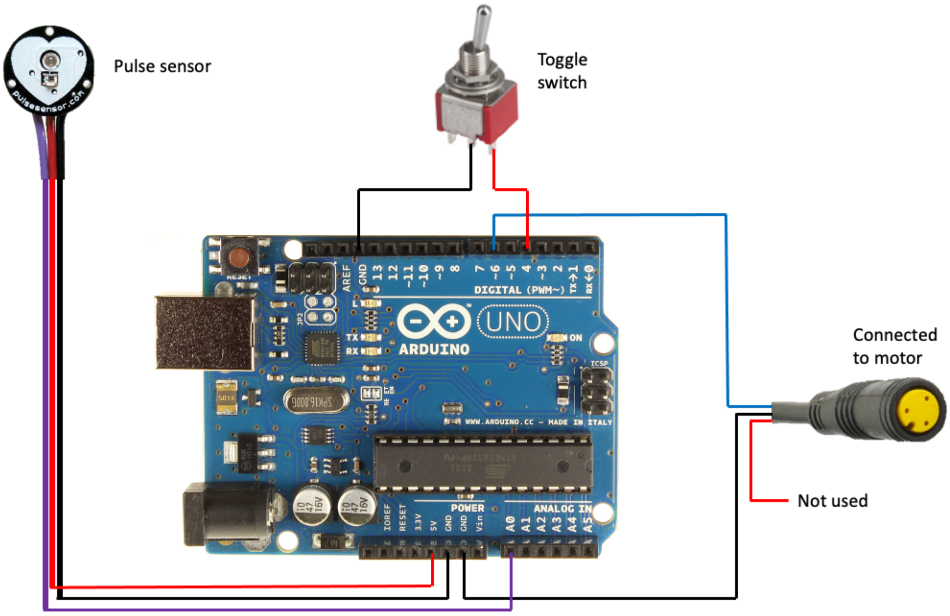


Figure 2.5: Wiring diagram of motor system with PPG sensor.

Figure 2.6: Setup of motor control with PPG sensor.

2.5 Third idea - motor speed control by accelerometer

The third idea that was explored further was motor speed control by an accelerometer. The first idea in section 2.3 is a way of controlling the motor using an external object, the pole. This means that the poles would have to be sold with the sit-ski. A more practical solution would be to incorporate the motor control unit *in* the sit-ski. This should be possible, as the same forces that act in the poles are transferred to the sit-ski. To explore this idea an accelerometer of the type LIS3DH [34] was used. The wiring diagram of the electronic system can be shown in figure 2.7. An SD-card module from Sparkfun OpenLog with an ATmega328 microcontroller chip [35] was used to save the data. To test the electronic setup, the system was attached to a chair, see figure 2.8a. A test subject was placed in the chair and instructed to pole down the hallway, approximately 10 meters, to get a data set.

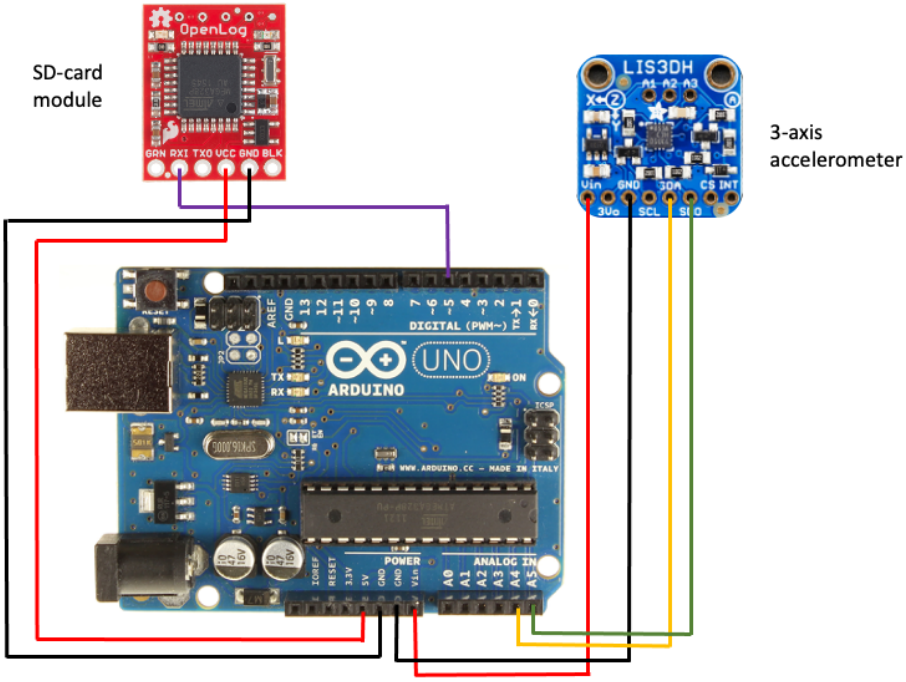
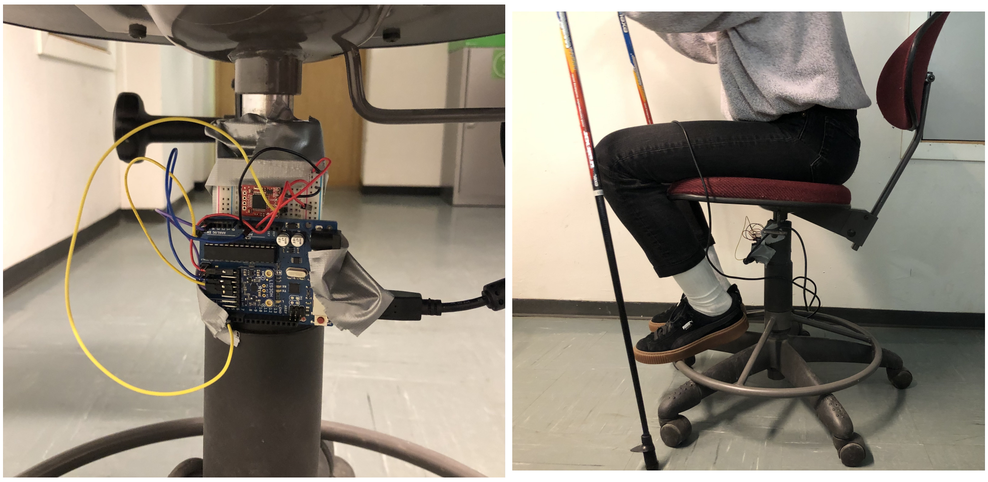
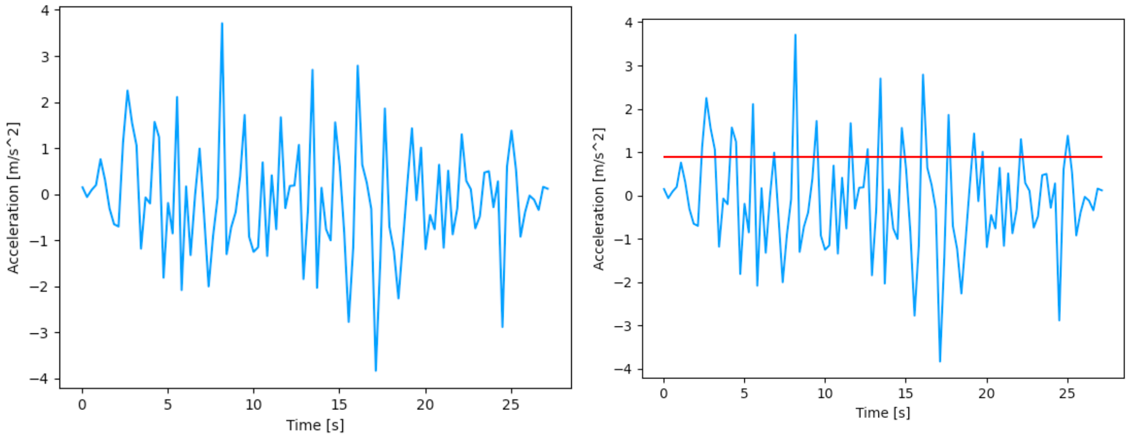


Figure 2.7: Wiring diagram of motor system with accelerometer.



(a) Accelerometer attached to chair. **(b)** Person sitting in chair and poling.

Figure 2.8: Setup of accelerometer attached to chair.



(a) Accelerometer attached to chair.

(b) Acceleration with threshold of 0.9 m/s^2.

Figure 2.9: Data from poling with the accelerometer on chair.

Figure 2.9 shows the accelerometer data in the direction that the chair was moving. A way to use this data to control the motor speed is to define a threshold and therefore establish the frequency of the poling motion. The frequency can be used to determine how much motor help the user should get. An example is more motor help at higher poling frequencies. In figure 2.9b there is an example of a threshold set to 0.9 m/s^2.

Chapter 3

Development of PPG motor control concept

In the previous chapter, three ideas were explored as concepts of controlling the motor speed. After generating multiple problem solutions, it is time to move into the decision-making aspect [20]. A natural way to progress would be to choose one of the ideas to work on further and improve. However, another option is to combine all the solutions into one. Consequently, this would lead to a large amount of quantitative data that can be used to: (1) evaluate the system and (2) improve the system. The load cell will provide poling force data, the PPG sensor will gather HR data and the accelerometer will measure the acceleration forces. In addition, the Arduino will provide data of time and whether the motor is getting power.

The following section describes how the three ideas were combined into one operating motor control system. After the setup, the system was tested two times in Granåsen on snow. The first test did not gather any data, but the system got improved from the lessons learned. The second test is described in section 3.2 and consists of the following subsections: method (3.3.1), results and discussion (3.3.2) and conclusion (3.3.3).

3.1 Combining the three ideas together

Controlling the motor speed using HR data opened up a new direction in the project. What if the sit-ski could be used as a rehabilitation tool? During rehabilitation, the user wants to keep a steady HR while exercising. As described in the Introduction, section 1.3, submaximal exercise is common in rehabilitation practices. An example of an exercise is to keep the pulse under 120 beats per minute (BPM). By controlling the motor using BPM, the user could get more motor help when the HR becomes higher and less when the HR slows down.

An important note is that the sit-ski should be an activity aid, not a snowmobile. To prevent this from happening, the motor control system has to facilitate movement, in this instance poling. By using the load cell in the pole as a power transfer signal, this can be assured. If there is compression forces on the sensor, the motor will get power. If not, the motor will stop. Similarly to an electric bike the motor will not help the user if he/she is not pedaling. This will prevent the sit-ski from becoming a motor vehicle. How this is done is shown in figure 3.1. The threshold of motor activation is 2 kg. When the filtered load value (blue line) exceeds the threshold (red line), the motor gets power (yellow line). The motor activation is represented as a binary number in this figure.

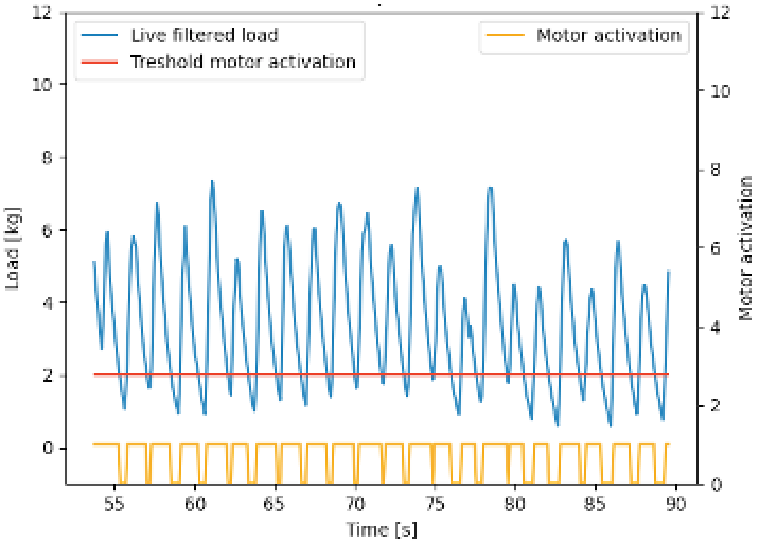
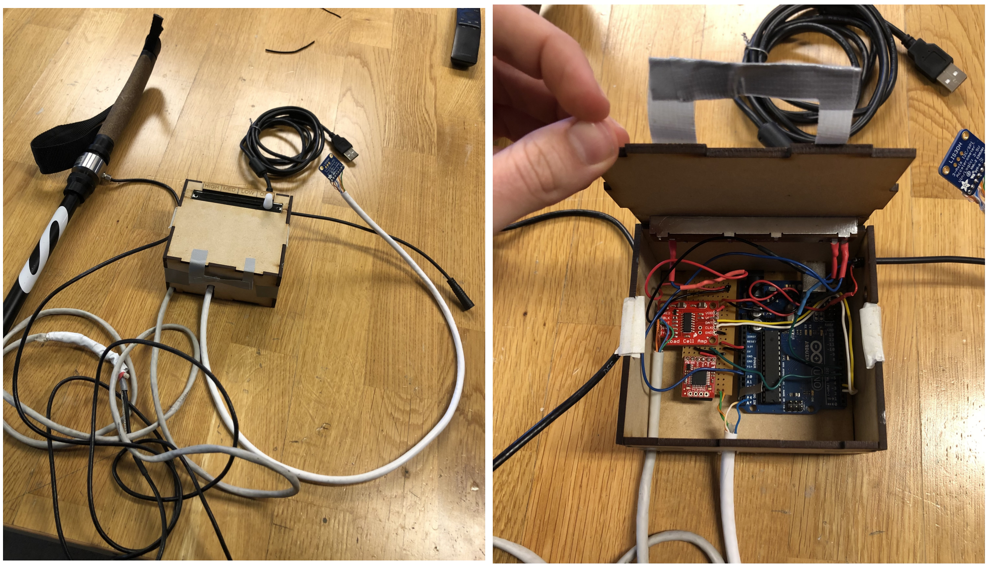


Figure 3.1: Plot of filtered load cell data with a threshold of 2 kg for motor activation



(a) How the system looks. **(b)** Box with electronics.

Figure 3.2: PPG motor control system.

The PPG motor control system can be seen in figure 3.2. The box of electronics was made by laser-cutting and gluing 6mm mdf-plates for a quick and relatively robust solution, as shown in figure 3.2b. The purpose of the box was to protect the electronics and to avoid the wires from being torn apart. The wire drawing of the system can be seen in figure 3.3 and the code can be found in Appendix A, section A.0.5. The Sparkfun load cell amplifier was changed to see if the signal from the load cell could become less noisy.

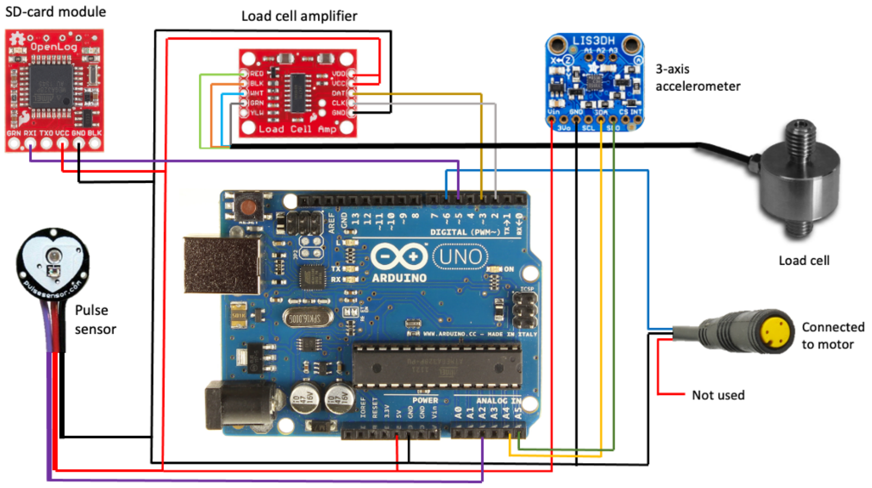


Figure 3.3: Wiring diagram of motor system with PPG motor control concept.

3.2 First test of PPG system on snow

The first test of the system on snow was conducted in Granåsen. The purpose of the testing was to gather quantitative data and evaluate if the system was viable as an aid in rehabilitation. However, the testing failed this day and this became an opportunity learn more about the system and to improve the sit-ski. The test subject was an able-bodied individual and is shown in figure 3.4. Once the test subject sat down on the sit-ski, the belt and motor did not move. The pressure on the belt was too big, so the motor did not turn. The pressure had to be distributed from the belt to the skis. A provisional solution was to put branches between the sledge and the skis to elevate the sit-ski, as shown in figure 3.5. The sit-ski worked for about 100 meters, until the motor stopped again. This time wet snow had come into the accelerometer and the electronic system shut down. While the belt was turning, snow was thrown forward straight into the electronic system.

Figure 3.4: Sit-ski with test subject.

Figure 3.5: Branch placed between the sit-ski and the skis.

The sit-ski had to be improved to be tested again. To prevent the snow from being thrown forward, a shield was mounted between the legs on the sit-ski as seen in figure 3.6a. The power-bank did not have any protection and was therefore vulnerable to get wet from the snow. A protective box was made for the power-bank, similar to the box for the other electronic parts. The accelerometer had to become waterproof, so a plastic film was taped around it as seen in figure 3.6b. Lastly, the sledge had to be elevated for the motor to be able to turn. This was done by replacing the temporary branches with mdf-plates, as shown in figure 3.6c. The sit-ski was ready for a new test.

(a) Shield between legs. **(b)** Taped accelerometer. **(c)** Mdf-plates replace branches.

Figure 3.6: Improvements after first test of PPG system.

3.3 Second test of PPG system on snow

With the improvements from the first test, the sit-ski was ready for a new test. The second test of the sit-ski was successful. This means that data was gathered and could be analysed. The next sections describes the method, results and discussion, and conclusion of the testing.

3.3.1 Method

The second testing of the system was also conducted in Granåsen. The main goal of the testing was the same as for the first test; to gather quantitative data that can be used to evaluate the applicability of the sit-ski in rehabilitation. The testing distance was 700 meters and had an average gradient of 0.04, see equation 3.1. The length of the slope is shown in figure 3.7. The test subject was an able-bodied individual and was told to pole for at least five minutes. In addition to the PPG sensor, the pulse was measured by a HR monitor and the data was recorded and stored in a Garmin watch. The electronic system described in section 3.1 measured the time, the BPM from the PPG sensor, the compression force in the load cell, the acceleration from the accelerometer and whether the motor was activated.

$$Gradient = \frac{Vertical\ change}{Horizontal\ change} = \frac{28\ m}{700\ m} = 0.04 \tag{3.1}$$

The test consisted of four runs, each run having a different level of help from the motor. The motor gives help according to the BPM of the user and the three levels of motor help are represented in table 3.1. The motor will give maximum help at the corresponding BPM-values, which means that the higher the level, the more motor help. The last run was taken with the belt completely disassembled.

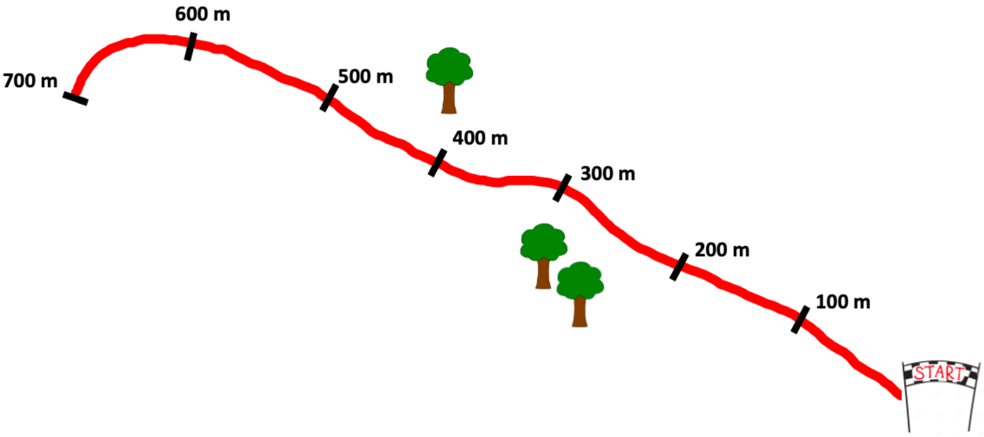


Figure 3.7: Length of slope.

Table 3.1: Motor help levels for PPG system.

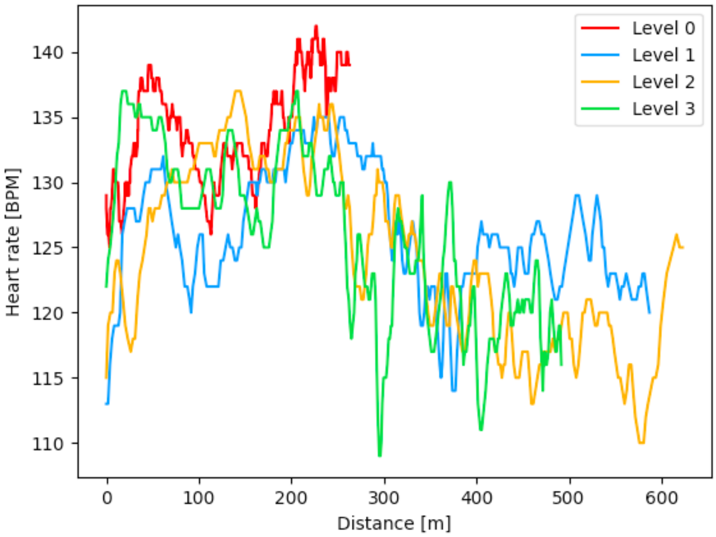
Level	**Maximum motor help at...**
Level 0	Motor and belt disassembled
Level 1	150 BPM
Level 2	125 BPM
Level 3	100 BPM

The data was smoothed using a Savitzky-Golay filter. Savitzky-Golay filter is a data smoothing filter that approximates the function by using a least-squares polynomial fit within a moving window [36]. The main purpose of data smoothing is to make it easier to read noisy data. The load cell was filtered live using an exponential filter and a filter that eliminated extreme values, see code in Appendix A, section A.0.2. The live filter also had the purpose of making the motor activation last longer than the time the pole is in the ground. The aim of this was to give the user a smoother experience.

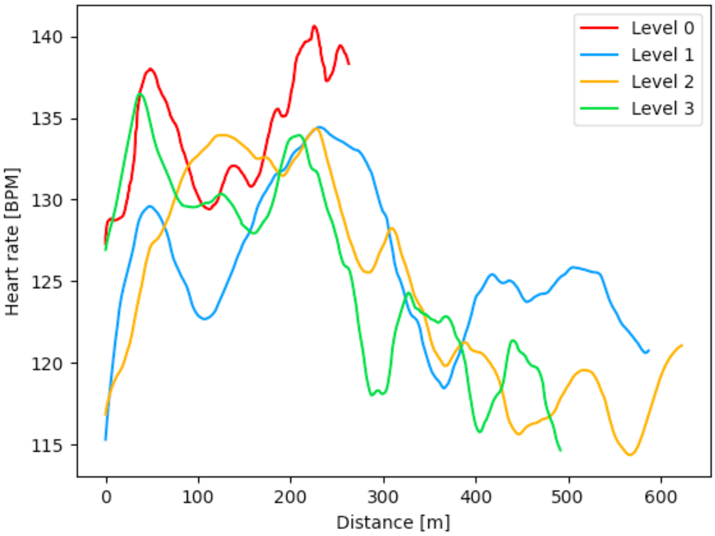
3.3.2 Results and discussion

Heart rate data

Figure 3.8 displays the BPM data from the Garmin watch plotted against the distance of the track for the different levels. The graph shows how far the test subject got after poling on the sit-ski for five minutes. The participant got the furthest in level 2 and the shortest when the belt was disassembled. Figure 3.8a shows the raw data, while 3.8b shows the smoothed data. The data is smoothed using a Savitsky-Golay filter with a moving window of 50 samples and a polynomial of degree three.



(a) Plot before smoothing.



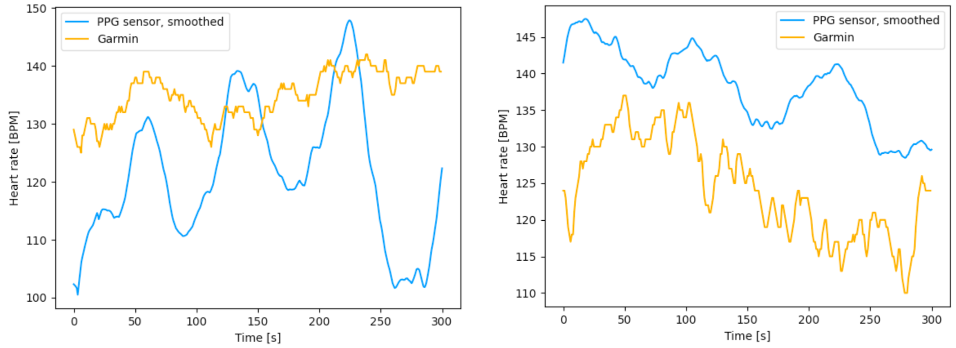
(b) Plot after smoothing.

Figure 3.8: Plot of BPM data from Garmin watch against distance.

The plot does not show a clear HR trend in the different levels. The pulse has the highest values when the belt is disassembled. However, right beneath is the line for level 3 that gives the test subject the most motor help. This line should have been on the lower part of the plot.

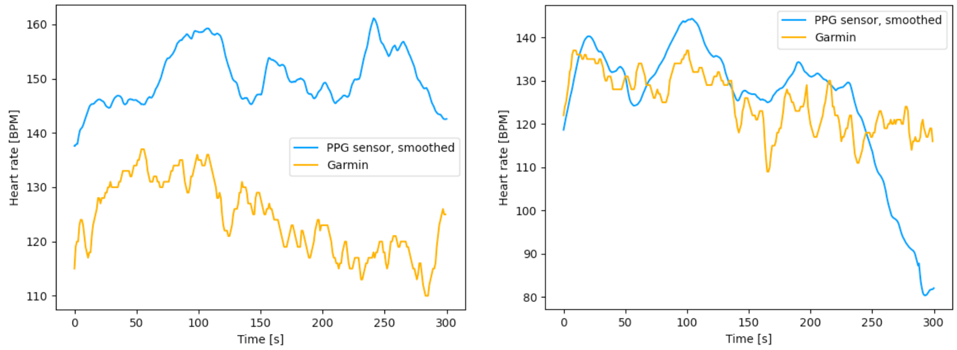
The difference in run length in the different levels are noticeable, particularly level 0. When the belt is disassembled, the participant manage to travel about half the distance as when the motor is assembled. The pulse is also considerably higher, especially in the uphill slope between 200-300 m. This shows how much more strenuous sit-skiing is without motor help.

An explanation of the unclear results can be the change in snow conditions. In the beginning of the test, the snow was soft and the belt did not have the best grip. Throughout the evening the snow hardened and became almost as solid as ice. Consequently, the belt got a better grasp of the snow. The first test run was with level 3, the second with level 2 and the third with level 1. The level 3-run had slush snow, which might have given less propulsion because of the lack of grip. At the same time, the level 1-run had icy snow with great friction and might have given more propulsion assistance at lower motor help.



(a) Level 0.

(b) Level 1.



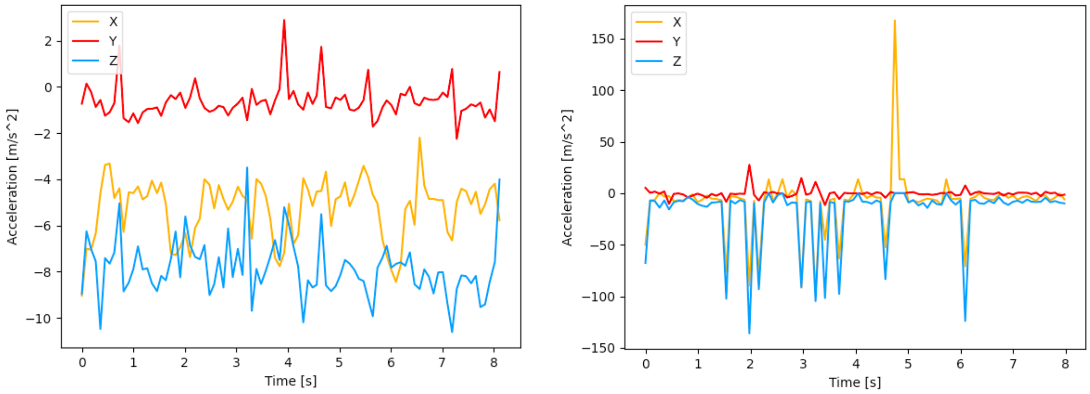
(c) Level 2.

(d) Level 3.

Figure 3.9: Plot of BPM data from Garmin watch and PPG sensor.

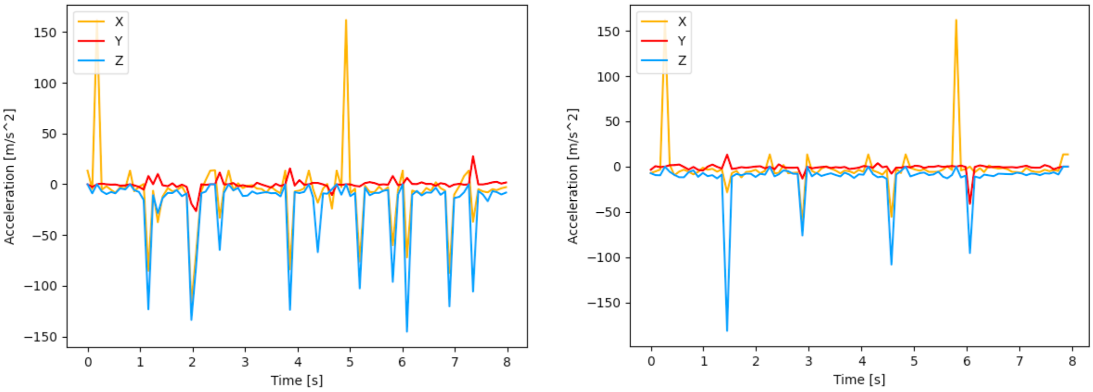
In figure 3.9, the BPM from the Garmin watch and the PPG sensor is plotted together. The PPG sensor data is smoothed using a Savitsky-Golay filter with 1000 samples in the moving window and a polynomial of degree two. Level 0, 1, 2 and 3 are shown in figure 3.9a, 3.9b, 3.9c and 3.9d, respectively. At level 0, the PPG sensor data moves up and down more rapidly than the Garmin data. It seems like the PPG sensor looses conctact and moves toward zero. The exponential filter makes the data move slowly towards zero, before the sensor gets back in contact with the HR reading and slowly moves towards the similar value of the Garmin watch. The plot in level 1 and level 2 are similar in the way that the PPG sensor has data that is systematically about 20-30 BPM higher than the Garmin data. It is hard to explain this error. It looks as if the PPG sensor does not have a high accuracy and this can be caused by multiple reasons. The earlobe clip might not sit hard enough on the ear or it might sit too tightly. The movement of the test subject could have caused inaccuracy in the light absorption, though this is more likely to explain the deviation in figure 3.9a. Since the PPG sensor consistently reads too high values of the pulse, the participant gets more motor help than it is supposed to have. Consequently, the pulse becomes lower than it is supposed to. This can be an explanation to why the HR data in figure 3.8 does not show a clear trend. Lastly, the BPM data in the level 3 plot is matching very well, until the end where the PPG sensor looses connection. The code could be improved by neglecting the measurements of the PPG sensor when it looses contact.

Acceleration data



(a) Level 0.

(b) Level 1.

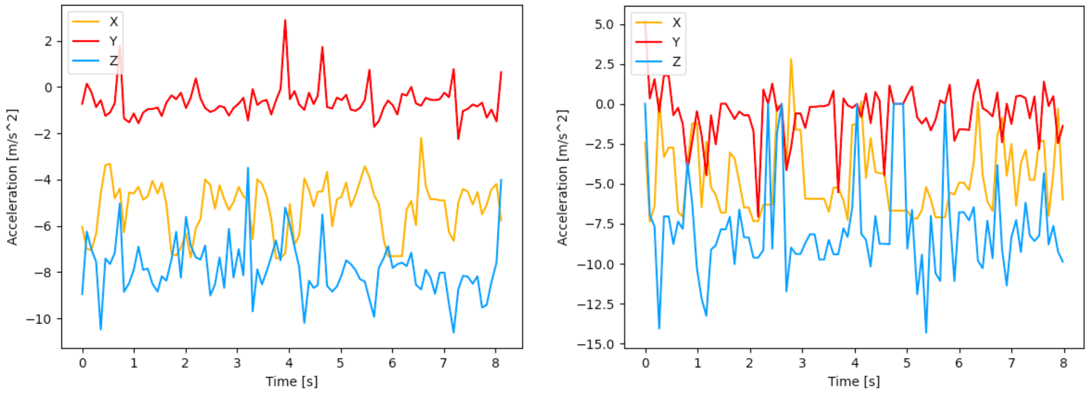


(c) Level 2.

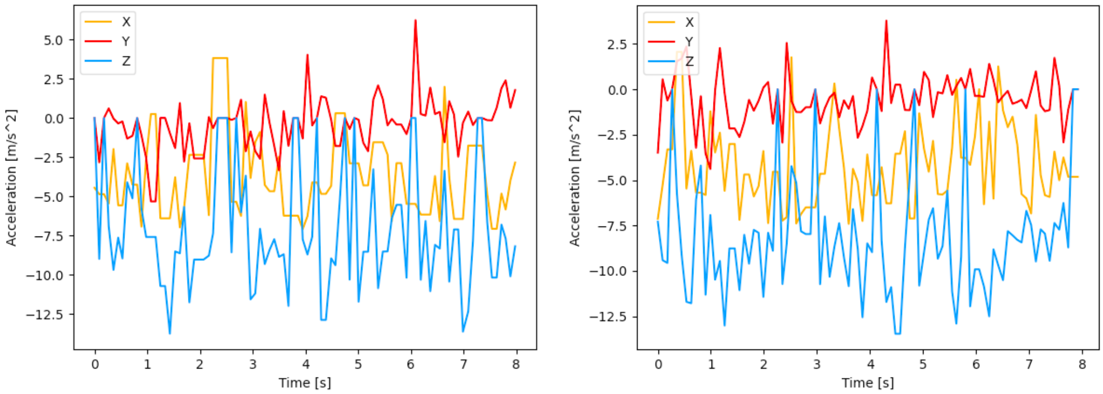
(d) Level 3.

Figure 3.10: Plot of raw acceleration data from accelerometer.

The raw acceleration data from the accelerometer are displayed in figure 3.10, showing the first eight seconds of each run. The data from level 0, 1, 2 and 3 are shown in figures 3.10a, 3.10b, 3.10c and 3.10d, respectively. All of the plots, except level 0, has high deviations in the measurements, such as $-100\ m/s^2$ or $-150\ m/s^2$. Post-process, a simple filter was put up to eliminate the noise of these values. If the absolute value of a measurement in the z-direction was over 15 m/s^2, the value was set to the previous measurement. The same was done for the x- and y-value at the threshold 7.5 m/s^2. The result of the filtering is shown in figure 3.11. After the most extreme jumps was eliminated, the data was still hard to read. At level 1, 2 and 3, the z-value constantly jumps down to 0 m/s^2, when it should be around 9.8 m/s^2. The y-value is perpendicular to the direction the sit-ski is moving and should be at around 0 m/s^2, except for when the sit-ski is turning. However, it fluctuates a lot. It seems as though the acceleration data in level 1, 2 and 3 is corrupted and that level 0 is the only data that is not. This makes it hard to compare the levels to each other. The corruption of the data could be caused by contact between the wires, either by physical contact or by water or snow getting into the accelerometer.



(a) Level 0. **(b)** Level 1.



(c) Level 2. **(d)** Level 3.

Figure 3.11: Plot of post-possessed acceleration data from accelerometer.

Lastly, the acceleration data in the x-direction was plotted in the same graph, see figure 3.12. It shows the first eight seconds of the runs. Again, it is hard to draw any conclusions since the data seems corrupted. It does not appear as if any data smoothing can save this data either. The x-values are negative since the x-axis is pointing in the opposite direction to the movement of the sit-ski. The x-direction is the most interesting to look at, since it is the same axis that the sit-ski moves in. It is stilt interesting to plot all the directions together, since the y- and z- value can give information about the quality of the measurements. Because the data in all directions is noisy, it is hard to trust that this data is accurate enough to draw any conclusions.

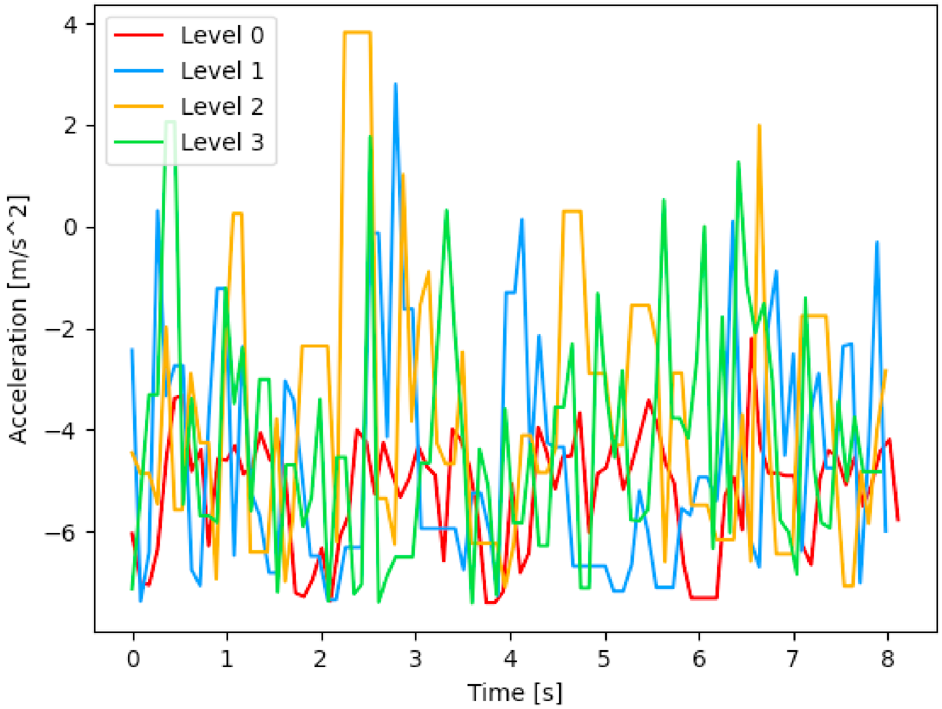
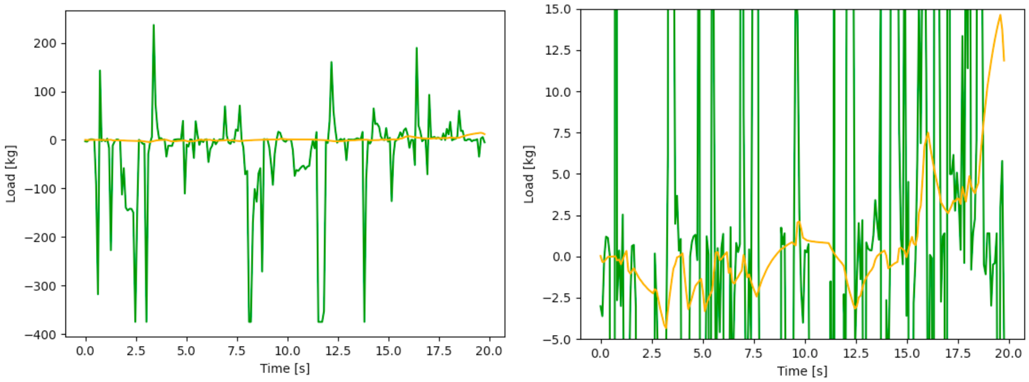


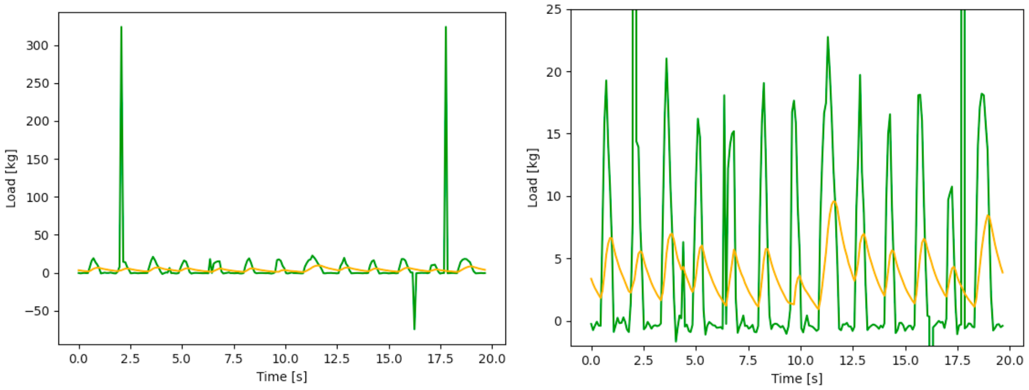
Figure 3.12: X-direction of the filtered acceleration data.

Load cell data

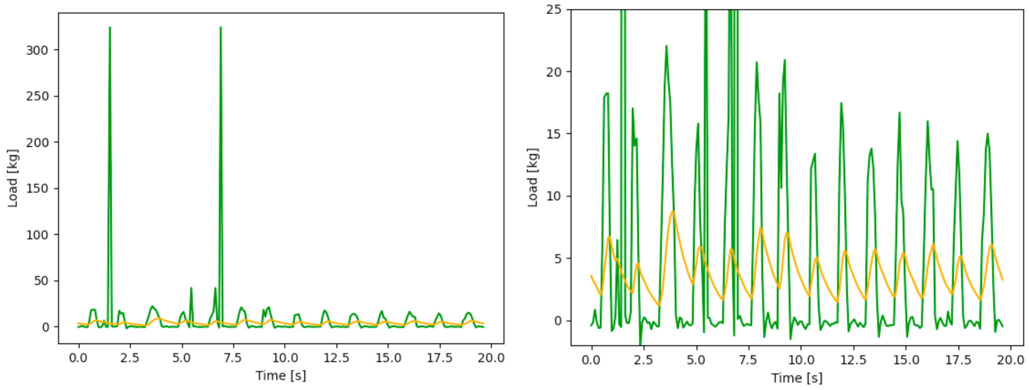
Figure 3.13 shows the load cell data. The left side of the figure displays the live filtered load data is plotted together with the raw load data. Since it can be hard to read the data, the right side of the figure zooms in on the plots. The wire to the force sensor got worn out during the testing since each time the user poled, the arm touched the wire. This is why the results in level 0 are unreadable. The poling forces in level 1 had the highest values, which means that the test subject used more power during the poling in this time frame. In level 2 and 3, the subject seems to use about the same amount of forces. The plots clearly shows how the filter is delaying the load values from going directly back to zero.



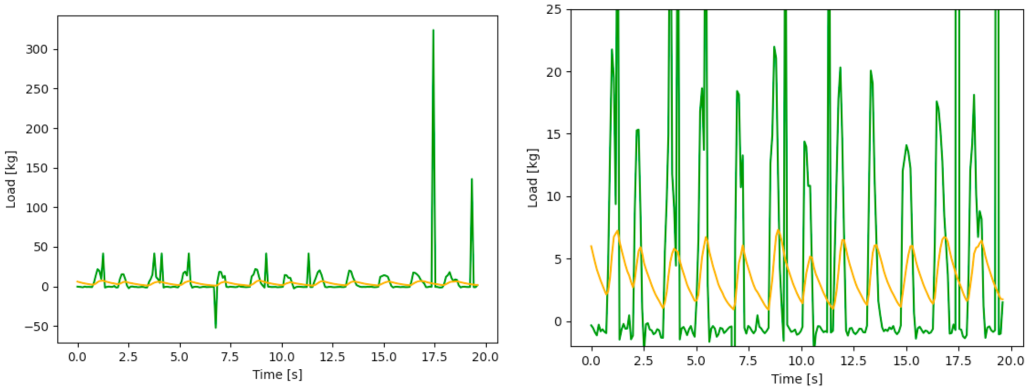
(a) Level 0. **(b)** Level 0 - zoomed in.



(c) Level 1. **(d)** Level 1 - zoomed in.



(e) Level 2. **(f)** Level 2 - zoomed in.



(g) Level 3. **(h)** Level 3 - zoomed in.

Figure 3.13: Load cell data.

3.3.3 Conclusion

The PPG sensor in this test recorded quite inaccurate HR data. Firstly, the sensor would loose contact with the ear and become zero. Better filtering of the data could have avoided this. Secondly, the sensor had a consistent higher HR in level 1 and 2. The reason for this is unclear. To conclude, there should be taken new tests with the sensor or the sensor should be switched out with another HR sensor. Further, most of the accelerometer data was corrupted. This could have been caused by contact between the wires. Therefore, it was hard to compare the levels or draw any conclusions this. Lastly, the load cell showed that level 1 had the most powerful poling. The difference between level 2 and 3 was small. The load cell became destroyed during level 0, so the data was corrupted. Due to the inaccurate HR-measurements, the system can not be used for rehabilitation purposes.

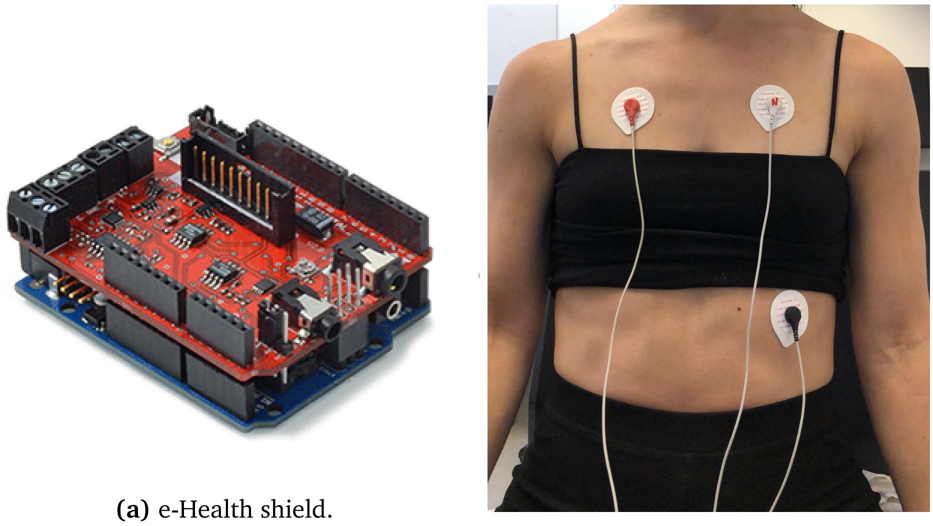
Chapter 4

Development of ECG motor control concept

Due to the inaccuracy of the PPG sensor, it was decided upon trying to switch it out with an ECG sensor. To learn more about how the ECG sensor operated, two preliminary tests was conducted. The first, in section 4.1.1, was to figure out which placement of the electrodes was the best. The second, in section 4.1.2, was to establish how vulnerable the sensor was to movement. Then, the system was ready for a test with the sit-ski on snow. This is described in section 4.2 and includes method, results and discussion, and conclusion.

4.1 Preliminary testing of the sensor

ECG is short for electrocardiogram and it is a tool that measures the electric activity in the heart [37]. The HR can be calculated from the ECG waves. To get familiar with the sensor, preliminary testing was conducted.



(a) e-Health shield.

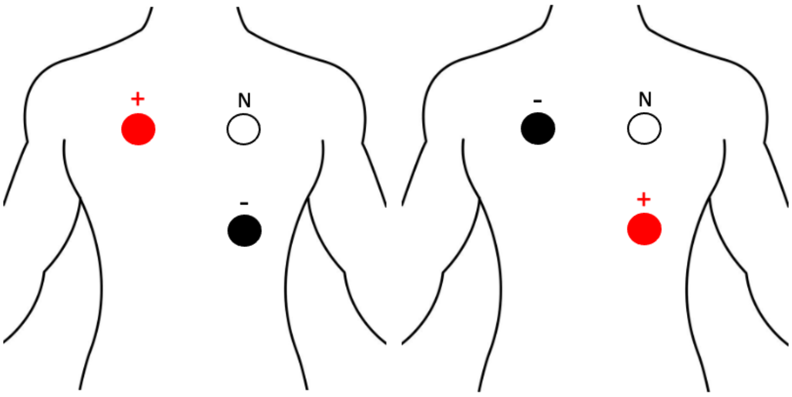
(b) Example of electrode placement.

Figure 4.1: ECG shield and placement of the electrodes.

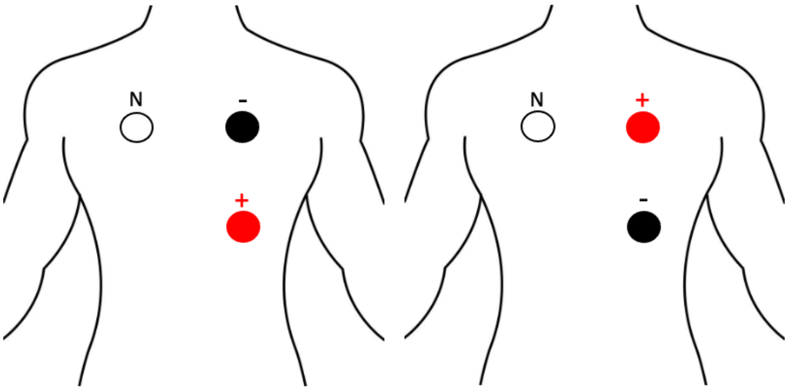
The preliminary testing system consists of an Arduino Uno and an e-Health Sensor Shield V2.0 that measures the ECG [38]. An Arduino shield can be placed on top of the Arduino board, see figure 4.1a, and broaden its applicability. There are three electrodes; a positive, a negative and a neutral, and these are attached to the test subject. An example of how the electrode can be attached to a test subject is shown in figure 4.1b. The disposable electrodes used in this project are Harmonwell TF55 electrodes with a teardrop shape of foam and aqua-tac gel that sticks to the skin [39].

4.1.1 The first test: placement of electrodes

There are various ways of placing the electrodes on the torso and this can result in different signals. Four different positions was tested to see how the signals differentiated and which position that gave the strongest signal. Figure 4.2 displays the different positions that was tested. The first was with the positive electrode on the upper right side of the torso, the neutral on the upper left side and the positive on the lower left side, as in figure 4.2a. In the second position the positive and negative electrode change places, as in figure 4.2b. Figure 4.2c shows the third positioning, where the neutral and negative electrode change places. Lastly, the firth position in figure 4.2d is with the neutral electrode on the upper right, the positive on the upper left and the negative on the lower left.



(a) Placement 1 **(b)** Placement 2



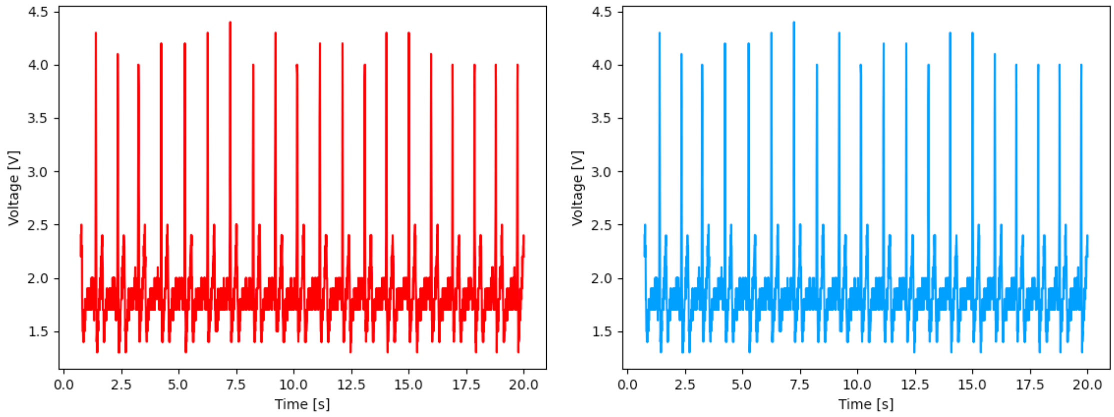
(c) Placement 3 **(d)** Placement 4

Figure 4.2: Different placement of the ECG electrodes.

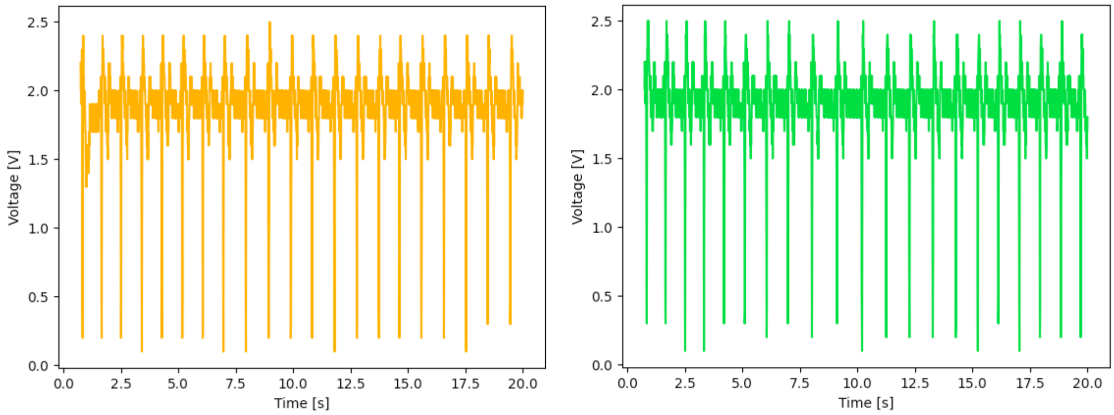
The attachment of the electrodes was done in the following way:

1. Took a cotton pad and cleaned the skin with rubbing alcohol. Made sure the skin was dry and free of excessive hair.
2. Connected the electrodes to the wires.
3. Removed the plastic film on the electrodes and placed the electrode on the skin. Rubbed the foam with the finger to make sure it was attached properly.

Figure 4.3d displays the ECG data from the different positions. Figure 4.3a, 4.3b, 4.3c and 4.3d shows position 1, 2, 3 and 4, respectively. Every position gave a clear signal and the signals were very similar. The most noticeable difference is that the peaks turn the opposite way in position 1 and 2 compared to position 3 and 4. As all the positions gave clear signals, it does not seem to matter which position is chosen for further testing. So, position 1 was selected.



(a) Position 1 **(b)** Position 2



(c) Position 3 **(d)** Position 4

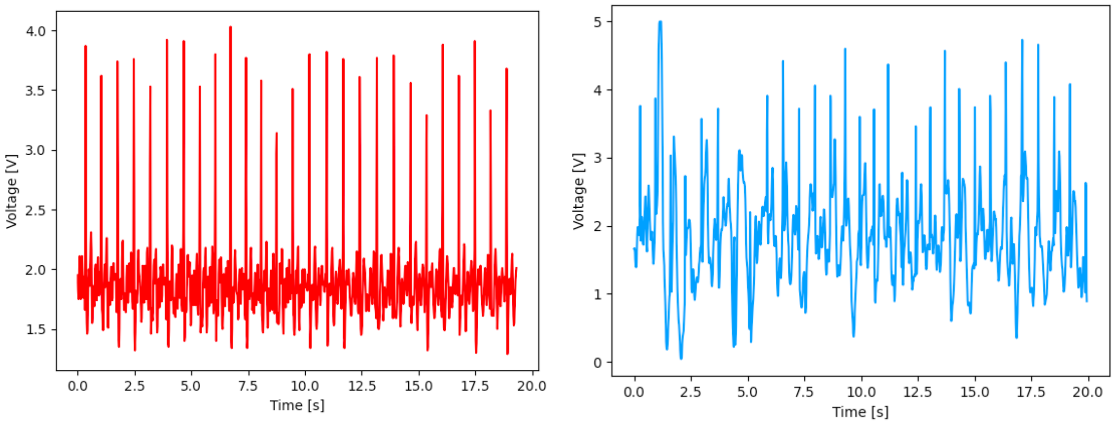
Figure 4.3: Plot of ECG data for different placements of the electrodes.

4.1.2 The second test: vulnerability to movement

The ECG sensor is going to be measuring HR data while the user is poling, so it is crucial to find out if movement affects the measured values. To evaluate this, four different movements were assessed to see if they would affect the measuring values. The movements were performed while sitting on a chair and they are described in table 4.1. The electrodes were attached to the participant in position 1.

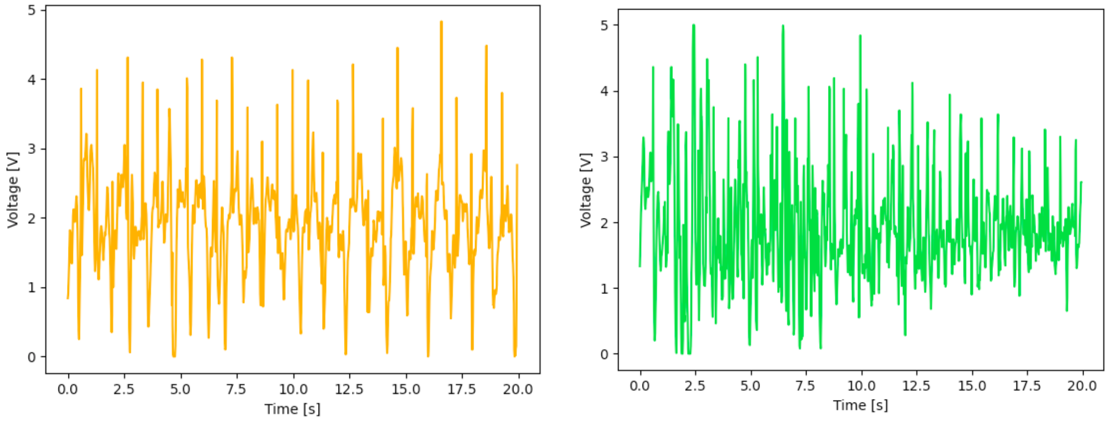
Table 4.1: Different movements tested while sitting on a chair.

Number	Type of movement
1	Sitting still
2	Poling with the upper body
3	Moving legs up and down (walking motion)
4	Shaking the wires



(a) Movement 1

(b) Movement 2



(c) Movement 3

(d) Movement 4

Figure 4.4: Plot of ECG data for different movements.

The results are displayed in figure 4.4. Movement number 1 in figure 4.4a shows the ECG data from when the test subject is sitting still. This signal is clear and resembles the signals from the first testing in section 4.1.1. In movement number 2, figure 4.4b, the signal becomes less clear. This is a similar motion to double poling on the sit-ski. Moreover, movement 3 causes a similar disruption of the

ECG signal, as shown in figure 4.4c. Figure 4.4d displays how the signal is affected when the wires are shaken. The signal becomes very noisy compared to 4.4a. It seems as if the shaking of the wires has the most negative impact on the signal. To prevent this from happening, the wires should be secured during testing.

4.2 Test of ECG system on asphalt

4.2.1 Method

The wiring diagram for the ECG motor control system can be seen in figure 4.5. The system consists of the same Arduino shield as described in section 4.1, but now the load cell and motor connection is added. The voltages that the ECG measures are very low and the measurements are therefore prone to disruption. During the setup of the system, it became clear that the accelerometer interrupted the ECG signal. Therefore, it was decided upon eliminating the acceleration sensor.

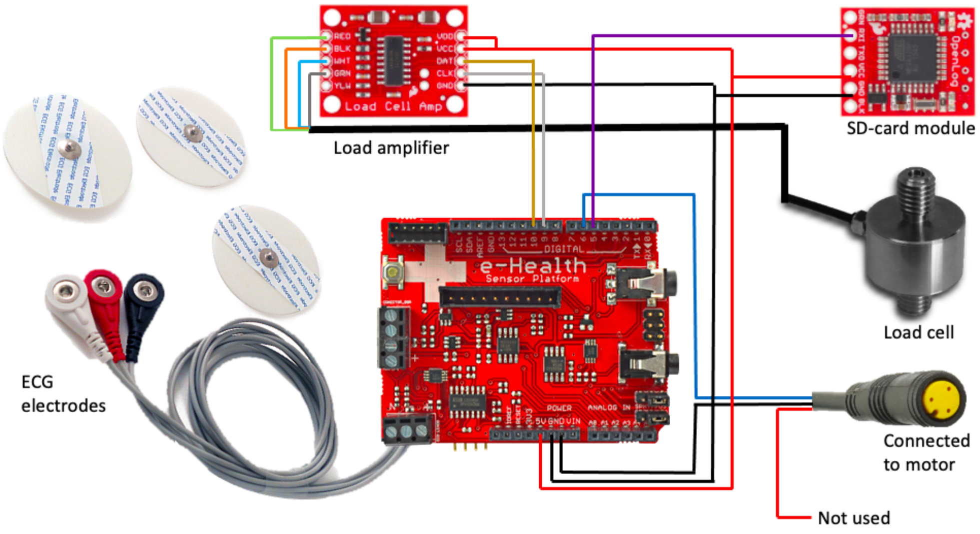


Figure 4.5: Wiring diagram of ECG motor system.

The ECG system was tested on asphalt using roller skis since the snow had melted. To proceed, the BPMhad to be calculated from the ECG data. A threshold of 2.7 was chosen to detect the peaks. Figure 4.6 shows the threshold plotted with the ECG data from position 1. To find the BPM, the time between two peaks, t_{peak}, are calculated in milliseconds. After that the following equation is used:

$$BPM = \frac{1000\ ms}{t_{peak}} \times 60\ s \tag{4.1}$$

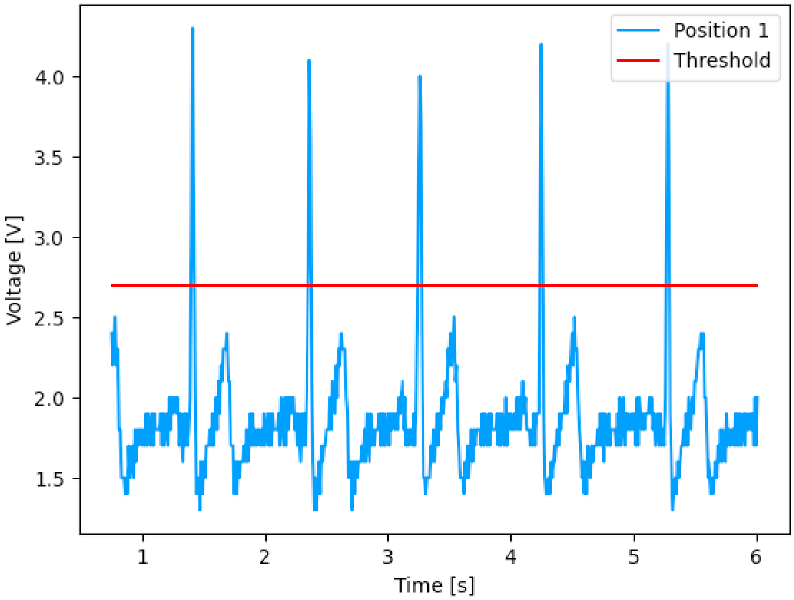


Figure 4.6: Plot of ECG data in position 1 with threshold of 2.7.

Figure 4.7: A picture of the test run.

The test run was an 80 meter long hill with a low gradient. The gradient is calculated in equation 4.2. A picture from the test run is attached in figure 4.7. The slope has a slight turn to the left. Before each run, a new set of electrodes were attached to the test subject. The attachment of the electrodes was done as described in section 4.1.1.

$$Gradient = \frac{Vertical\ change}{Horizontal\ change} = \frac{1\ m}{80\ m} = 0.01 \tag{4.2}$$

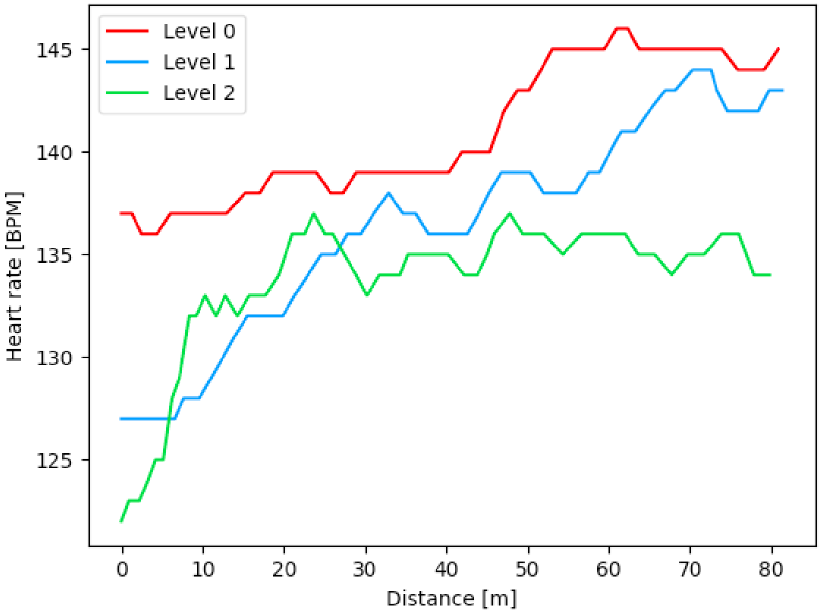
New levels were defined for this test, see table 4.2. The levels was cut to from four to three and the maximum BPMwas changed. The reason why the maximum BPM had to be altered was because the belt had a very good grip on the asphalt, causing the sit-ski to propel too fast forward for the test subjects comfort. The test subject was an able-bodied individual. Lastly, the broken load cell from the PPG sensor test had to be re-soldered. The angle of the wire was turned, so that the arm did not touch the cable while poling. Also, the wire was fixed to the pole to prevent it from being tugged on unnecessarily.

Table 4.2: Motor help levels for ECG system.

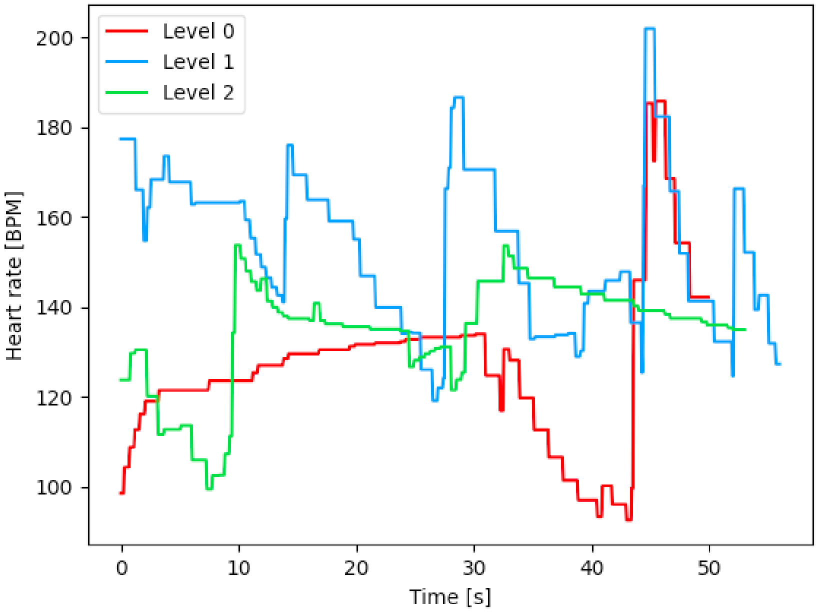
Level	**Maximum motor help at...**
Level 0	Motor and belt disassembled
Level 1	270 BPM
Level 2	200 BPM

4.2.2 Results and discussion

Heart rate data



(a) Data from the Garmin watch.

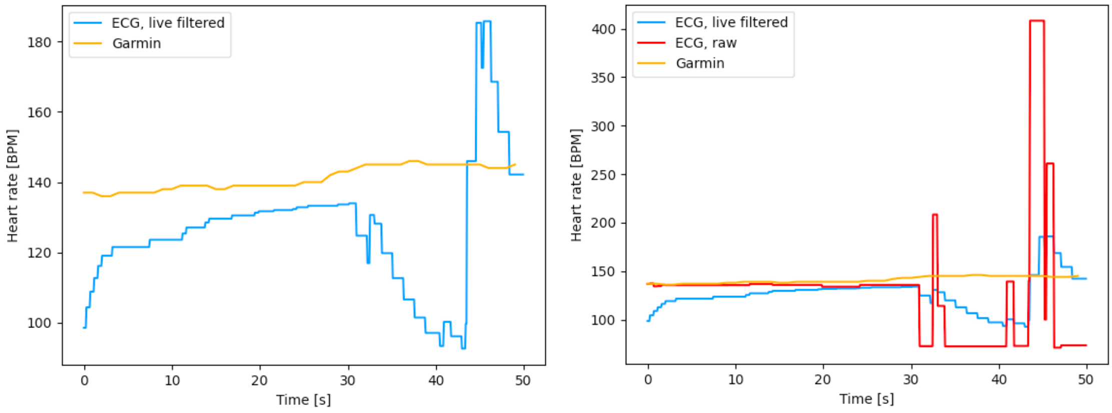


(b) Live filtered data from the ECG sensor

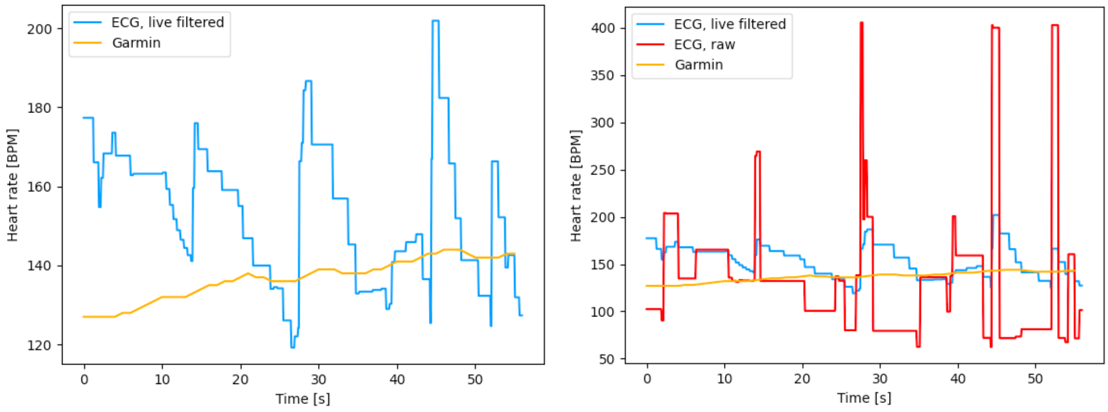
Figure 4.8: BPM data from the Garmin watch and ECG sensor from the test on asphalt.

The HR data is represented in figure 4.8. The data from the HR monitor connected to the Garmin watch is shown in figure 4.8a and the HR data from the ECG sensor in figure 4.8b. The HR from the HR monitor shows that the pulse is the highest for level 0. Underneath it is level 1, and the level with the lowest HR is level 2. Level 2 surpasses level 1 in the beginning of the run. The HR in level 2 seems to stabilize at around 135 BPM, while the HR in level 1 continues to increase. The HR data from the ECG sensor is more chaotic. Level 1 still has a higher HR than level 2. The measurements on level 0 from the ECG sensor was very inaccurate. These measurements was not connected to any motor, so it did not affect the motor activation in any way. An explanation for the inaccurate HR graph is that poling without a motor requires more effort and therefore more movement. This movement could have affected the signal. The duration of the test was quite short. To get more robust data, a new and longer test should be executed.

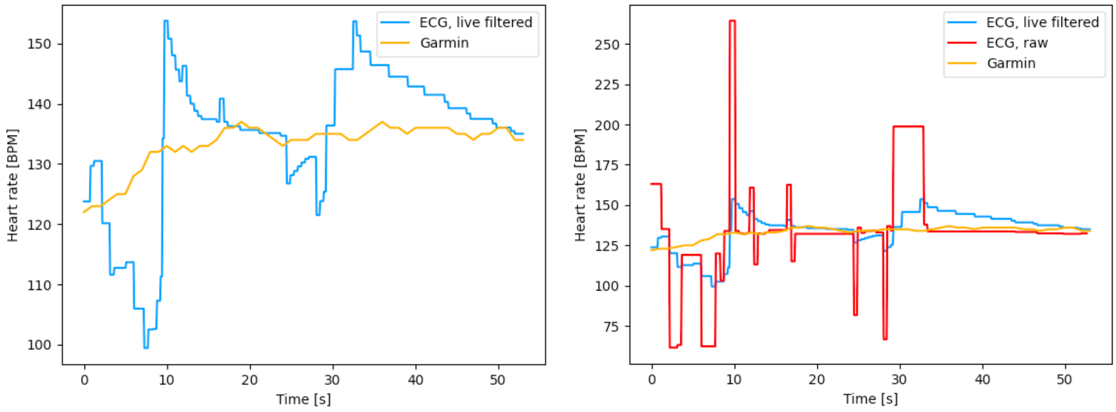
Figure 4.9 shows the HR data separated into the different levels. On the left side is the Garmin HR data and the live filtered ECG HR data plotted together. On the right side it is the same, but in addition the raw ECG HR data was added. It is clear that the filter does a good job eliminating the extreme values from the raw ECG HR data. In level 0 in figure 4.9b, the ECG HR graph follows the Garmin graph well during the first 30 seconds, until there is some disturbances. The same can be said for the end of the graph in level 2, figure 4.9f. The graph showing level 1 in figure 4.9d has many jumps up and down, but in between the jumps the BPMseems to align with the Garmin HR value. The filter uses some time to get back down after a big jump up. This data could have benefited from a better filter. The Garmin HR data has a built-in filter, which is clear to see as the graph is noticeably smoother than the ECG HR data.



(a) Level 0 **(b)** Level 0



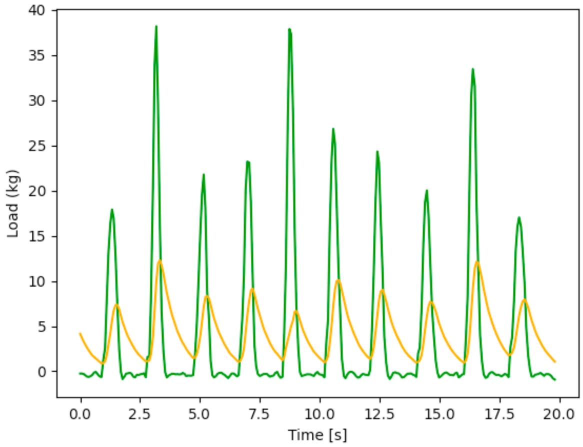
(c) Level 1 **(d)** Level 1



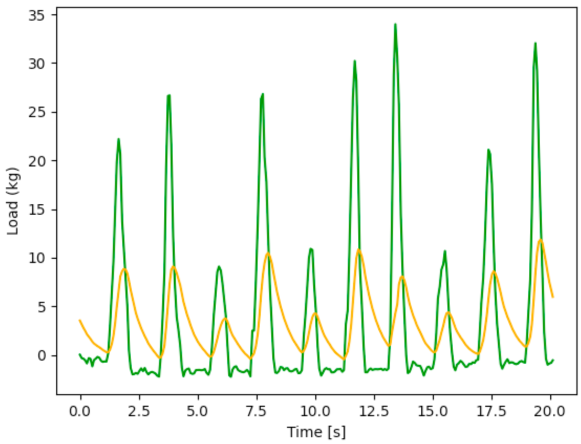
(e) Level 2 **(f)** Level 2

Figure 4.9: Plot of BPMdata, without (left) and with (right) the raw data from the ECG.

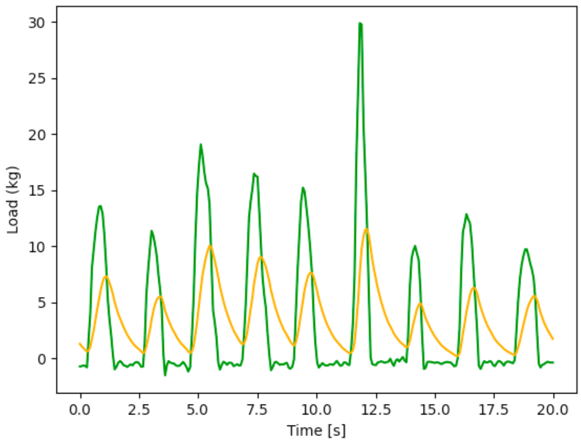
Load cell data



(a) Level 0



(b) Level 1



(c) Level 2

Figure 4.10: Plots of raw (green) and live filtered (orange) load cell data.

The load cell data is represented in figure 4.10. Level 0, 1 and 2 are described in figure 4.10a, 4.10b and 4.10c, respectively. The green line displays the raw load cell data, while the orange line represents the live filtered load cell data. The forces are the smallest in level 2, with an estimated mean of 12 kg per poling cycle. One value deviates from the rest, and that is the value of 30 kg at 12 seconds. This could be a poling cycle of when the test object turns. Since the slope of the test run curves to the left, the test subject has to use its body weight and the poles to turn the sit-ski to the left. The poling motion in level 1 is a bit irregular, with the values going up and down frequently. Since the ECG HR data also was quite irregular in this level, the motor might have given uneven help. Level 0, seen in figure 4.10a, has the highest load values, with a mean of approximately 20 kg. This is sensible since the poling gets harder without the motor help. The filter works nicely, as it delays the motor activation in an tidy manner.

4.2.3 Conclusion

This system is viable for rehabilitation purposes, as the HR varied synchronous to the different levels. Experimentation on which settings gives the different HR levels will be needed. The HR measurements might need a different or stronger filter that can eliminate the variations. The load forces in the poles was the greatest for the level without motor help, level 0, and smallest for the level with the most motor help, level 2. The live filtering of the load cell data worked as desired. The testing should have been conducted over a longer time span to get more robust data.

Chapter 5

Discussion

To conclude this master's thesis the objectives of the thesis will be systematically discussed. As the specific results from the testing was discussed at the end of chapter 3 and 4, this will be more of an overall discussion.

- Explore the possibilities of sit-ski motor speed control

In the beginning of the thesis, a range of different ideas was created. Further, three ideas was explored. The load cell idea was an obvious first choice, since the force data from the poling is a great way to measure poling forces and frequencies. However, continuing with this idea without trying any other ideas would not have been *exploration*. The PPG sensor system was more of a novel idea, since according to literature, nobody has tried to control motor speed using HR. Lastly, the accelerometer idea was an attempt to incorporate the motor control *in* the sit-ski. This objective was covered to a high degree, as there was an exploration in the different ideas instead of going for the first idea.

- Build and test a motor speed control concept

Two motor concepts was built: (1) the PPG motor control concept and (2) the ECG motor control concept. Data from testing of the different motor control system was gathered. This was limited to quantitative data. The thesis could have been more complete with qualitative data from users. This would have been a good way to test how the motor control system was perceived for them. However, the systems was in an early state phase, so more testing should be conducted before testing the system on disabled users. The degree of achievement on this objective was good, as there was a high level of quantitative data, but not qualitative data.

- Investigate the possibility of using the solution for rehabilitation purposes

For this sit-ski to be used as a rehabilitation tool, the pulse measurements has to be accurate enough to control that the user is working in submaximal HR conditions. The PPG sensor was a more practical solution than the ECG electrodes, since it was one ear-clip instead of three electrodes that had to be attached to a clean skin-surface. However, the PPG sensor gave some inaccurate HR measurements. This system should have been tested further to find out why there was inaccuracies and to find out if they were fixable. The ECG gave more accurate HR measurement, but the setup was unpractical. It would be a bonus if the solution became more practical for the user. A possibility could be to connect the sit-ski to the HR monitor and the Garmin watch, and use the live HR data from the watch to control the motor speed. This might lead to higher precision and more practical HR measuring.

Chapter 6

Conclusion and further work

The following section aims at concluding this thesis and addressing the next steps in the continuation of this work.

This thesis had the aim of developing a motor control system for a cross-country sit-ski that could be used for rehabilitation purposes. The idea of using HR as a means for motor speed control was novel and challenging to execute. HR data is not easy to measure on a test subject that is in movement. The PPG sensor gave inaccurate measurements, but the system might have potential if further testing is conducted to find out more about where the weakness of the measurements are. The ECG system gave more accurate HR data and can therefore be used for rehabilitation purposes.

The motor speed control concept developed in this thesis is an improvement from the thumb throttle solution of the previous master's thesis. The motor help becomes an organic part of the poling motion, which is important for making the experience pleasurable for the user.

In the continuation of this work, the sit-ski should be developed into a commercial product so that it can be accessible to the users. To do this, different materials and manufacturing methods has to be examined. The HR motor control concept matches the purpose of rehabilitation, but might be too specific for the average user. The load cell or the accelerometer concept might be a more practical solution if the propulsion assisted sit-ski should reach the marked. The motor control system needs to be tested on users that are in the relevant user group: individuals with leg impairments. A good product depends on their feedback. The belt-driven sit-ski has major potential as a product that can be used for rehabilitation or as an enjoyable leisure activity.

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Appendix A

Code listing

A.0.1 Code for accessing the motor using a potmeter

```
/* Accessing the motor using a potmeter to replicate signal from thumb throttle
 */

#define pot_pin A0
#define dig_output_pin 6
int value_slide_pot = 337;
int duty_cycle_value = 127;
int dig_output = 0;

void setup() {
  Serial.begin(9600);
  pinMode(pot_pin, INPUT);
  pinMode(dig_output_pin, OUTPUT);
}

void loop() {
  value_slide_pot = analogRead(pot_pin);
  Serial.print("Slide Pot value: ");
  Serial.println(value_slide_pot);
  duty_cycle_value = map(value_slide_pot, 0, 1023, 43, 220); //0.8V is 43 and 4.3V
    is 220, which is the same mapping as the thumb throttle
  Serial.print("Map value: ");
  Serial.println(duty_cycle_value);
  analogWrite(dig_output_pin, duty_cycle_value);
}
```

A.0.2 Code for motor speed control by load cell in pole

```
/* Load cell with HX711 amplifier with voltage output in PWM to be read by motor.

Amplifier to Arduino pins:
 2 -> HX711 CLK
 3 -> DOUT
```

```
 5V -> VCC
 GND -> GND

Output pins
6 --> PWM output to motor

*/

#include "HX711.h"  //You must have this library in your arduino library folder

#define DOUT  3
#define CLK  2
#define dig_output_pin 6

HX711 scale(DOUT, CLK);

//Change this calibration factor as per your load cell once it is found you many need to vary it in thousands
double calibration_factor = 22290; //-106600 worked for my 40Kg max scale setup

void setup() {
  Serial.begin(4800);
  Serial.println("Press T to tare");
  scale.set_scale(22290);  //Calibration Factor obtained from first sketch
  scale.tare();             //Reset the scale to 0
}

void loop() {
  double weigth = scale.get_units();
  double duty_cycle_value = 0;
  Serial.print("Weight: ");
  Serial.print(weigth, 3);  //Up to 3 decimal points
  Serial.print(" kg "); //Change this to kg and re-adjust the calibration factor if you follow lbs

  /*if(Serial.available())
  {
    char temp = Serial.read();
    if(temp == ’t’ || temp == ’T’)
      scale.tare();  //Reset the scale to zero
  }*/

  if (weigth < 0) {
    weigth = 0;
  }
  if (weight > 10) {
    weigth = 10;
  }

  duty_cycle_value = map(weigth, 0, 10, 0, 230);
  Serial.print(" Corresponding duty cycle value: ");
  Serial.println(duty_cycle_value, 3);
  analogWrite(dig_output_pin, duty_cycle_value);

```

```
}
```

A.0.3 Code for motor speed control by heart rate (HR) data from PPG sensor

```
/* Using PPG sensor as motor control

PPG sensor
5V - 5V
GND - GND
Analog output - A0

Toggle switch
Input - pin 4

Output pins
PWM output to motor - pin 6

*/


#define USE_ARDUINO_INTERRUPTS true    // Set-up low-level interrupts for most acurate BPM math.
#include <PulseSensorPlayground.h>     // Includes the PulseSensorPlayground Library.
#define PulseWire A0       // PulseSensor PURPLE WIRE connected to ANALOG PIN 0
#define MotorWire 6
#define BUTTON_PIN 4

//const int LED13 = 13;         // The on-board Arduino LED, close to PIN 13.
int Threshold = 550;           // Determine which Signal to "count as a beat" and which to ignore. Default value. Fine-tune in "Getting Started Project".
int toggle = 0;                 // Variable to store toggle value
int duty_cycle_value = 0;       // Duty Cycle Value (0 --> Volt output = 0 V, 255 --> Volt output = 5 V)

PulseSensorPlayground pulseSensor;  // Creates an instance of the PulseSensorPlayground object called "pulseSensor"

void correctBounds(int &variable) {
  if (variable < 20){
    variable = 20;
  }
  if (variable > 214){
    variable = 214;
  }
}


void setup() {

  Serial.begin(9600);          // For Serial Monitor

```

```
  // Configure the PulseSensor object, by assigning our variables to it.
  pulseSensor.analogInput(PulseWire);
  //pulseSensor.blinkOnPulse(LED13);       //auto-magically blink Arduino's LED with heartbeat.
  pulseSensor.setThreshold(Threshold);

  // Double-check the "pulseSensor" object was created and "began" seeing a signal.
  if (pulseSensor.begin()) {
    Serial.println("We created a pulseSensor Object!");  //This prints one time at Arduino power-up,  or on Arduino reset.
  }

  pinMode(BUTTON_PIN, INPUT_PULLUP);  //Toggle switch pinMode
}


void loop() {

int myBPM = pulseSensor.getBeatsPerMinute();  // Calls function on our pulseSensor object that returns BPM as an "int".
                                               // "myBPM" hold this BPM value now.
toggle = digitalRead(BUTTON_PIN);           //Read toggle value

if (pulseSensor.sawStartOfBeat()) {            // Constantly test to see if "a beat happened".
    Serial.println("A HeartBeat Happened! "); // If test is "true", print a message "a heartbeat happened".
    Serial.print("BPM: ");                        // Print phrase "BPM: "
    Serial.print(myBPM);                        // Print the value inside of myBPM.
    duty_cycle_value = (myBPM - 60) * (214 - 20) / (160 - 60) + 20;
    correctBounds(duty_cycle_value);
    Serial.print(" Corresponding duty cycle value: ");
    Serial.println(duty_cycle_value);

if (toggle){
    analogWrite(MotorWire, duty_cycle_value);
  }
}

  delay(20);                     // considered best practice in a simple sketch.

}
```

A.0.4 Code for motor speed control by accelerometer

```
/* Accelerometer and OpenLog code.

OpenLog
  RXI of OpenLog to pin 5 on Arduino
  VCC to 5V
  GND to GND

Accelerometer (IMU):
```

```
  SDA to pin A4
  SDL to pin A5
  Vin to 5V
  Gnd to GND

*/

//Openlog:
#include <SoftwareSerial.h>
SoftwareSerial OpenLog(0, 5); // 0 = Soft RX pin (not used), 5 = Soft TX pin

//IMU:
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_LIS3DH.h>
#include <Adafruit_Sensor.h>
#define LIS3DH_CLK A5
#define LIS3DH_MOSI A4

Adafruit_LIS3DH lis = Adafruit_LIS3DH();

//Time
unsigned long myTime;
float milliToSec = 1000;

void setup() {
  OpenLog.begin(9600); //Open software serial port at 9600bps
  //OpenLog.println("This serial records to the OpenLog text file");

  //Write something to OpenLog
  OpenLog.println("Test accelerator");

  if (! lis.begin(0x18)) {
    OpenLog.println("Couldn’t start");
    while (1) yield();
  }

  // lis.setRange(LIS3DH_RANGE_4_G);   // 2, 4, 8 or 16 G!
  OpenLog.print("Range = "); OpenLog.print(2 << lis.getRange());
  OpenLog.println("G");
}

void loop() {
    lis.read();      // get X Y and Z data at once
  // Then print out the raw data
  //Serial.print("X:  "); Serial.print(lis.x);
  //Serial.print("  \tY:  "); Serial.print(lis.y);
  //Serial.print("  \tZ:  "); Serial.print(lis.z);

  /* Or....get a new sensor event, normalized */
  sensors_event_t event;
  lis.getEvent(&event);

  //Print time
```

```
  OpenLog.print("Time (s): ");
  myTime = millis();

  OpenLog.print(myTime/milliToSec, 3); // prints time since program started

  /* Display the results (acceleration is measured in m/s^2) */
  OpenLog.print(" \tX: "); OpenLog.print(event.acceleration.x);
  OpenLog.print(" \tY: "); OpenLog.print(event.acceleration.y);
  OpenLog.print(" \tZ: "); OpenLog.print(event.acceleration.z);
  OpenLog.println(" m/s^2 ");

  OpenLog.println();

  delay(200);

}
```

A.0.5 Code for PPG motor control concept

```
 /* Load cell with HX711 amplifier with Voltage output in PWM to be read by motor.

Load cell Amplifier to Arduino pins:
 2 -> HX711 CLK (white)
 3 -> DOUT (yellow)
 5V -> VCC
 GND -> GND

Potmeter pin
 A0 --> Analog Output
 5V --> +
 GND --> -

Accelerometer (IMU):
 SDA to pin A4 (blue)
 SDL to pin A5 (orange stripe)
 Vin to 5V (green)
 Gnd to GND (orange)

SD-card
 RXI of OpenLog to pin 5 on Arduino
 VCC to 5V
 GND to GND

BPM:
 5V to 5V
 GND to GND
 Analog output to A1

Output pins
 6 --> PWM output to motor

*/

```

```
//Load cell
#include "HX711.h"
#define DOUT  3
#define CLK  2
HX711 scale(DOUT, CLK);
double calibration_factor {22290};
double load {0};
double filteredLoad {0};
const double smoothingConstLoad {0.1};
double noiseFilterLoad {0};
double storeLoad {0};

//Potmeter
#define potPin A0
int valuePot {0};
int potLevel {0};

//Accelerometer:
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_LIS3DH.h>
#include <Adafruit_Sensor.h>
#define LIS3DH_CLK A5
#define LIS3DH_MOSI A4
Adafruit_LIS3DH lis = Adafruit_LIS3DH();
unsigned long myTime; //Time
float milliToSec = 1000;

//SD-card
#include <SoftwareSerial.h>
SoftwareSerial OpenLog(0, 5); // 0 = Soft RX pin (not used), 5 = Soft TX pin

//BPM
#define USE_ARDUINO_INTERRUPTS true    // Set-up low-level interrupts for most accurate BPM math.
#include <PulseSensorPlayground.h>     // Includes the PulseSensorPlayground Library.
#define PulseWire A2       // PulseSensor PURPLE WIRE connected to ANALOG PIN 1
int sensitivityBPM{0};
const int Threshold{550};
int upperPulse{140};
int BPMMotorParameter{0};
double filteredBPM{0};
const double smoothingConstBPM{0.07};
PulseSensorPlayground pulseSensor;
double dutyCycleValue{0};

//Motor input
#define motorPin 6

//Functions
void maxPulseFromPotmeter (int potmeterValue, int &upperPulseVal, int &potLevelVal) { //Takes in value from potmeter to adjust how high max pulse is
  if (potmeterValue < 255) {
```

```
    upperPulseVal = 1000; //Put max pulse value to 500 to make the motor input very small
    potLevelVal = 0;
  }
  else if (potmeterValue > 255 && potmeterValue <=511) {
    upperPulseVal = 150;
    potLevelVal = 1;
  }
  else if (potmeterValue > 511 && potmeterValue <=767) {
    upperPulseVal = 125;
    potLevelVal = 2;
  }
  else if (potmeterValue > 767 && potmeterValue <=1023) {
    upperPulseVal = 100;
    potLevelVal = 3;
  }
}

void dutyCycleBoundaries (double &dutyCycle) { //Boundaries on duty cycle value
   if (dutyCycle < 0) {
    dutyCycle = 0;
  }
  if (dutyCycle > 210) { //Max is 220, but use 210 as safety margin to not overload the motor
    dutyCycle = 210;
  }
}

void setup() {
  //SD-card
  OpenLog.begin(9600); //Open software serial port at 9600bps

  //Potmeter
  pinMode(potPin, INPUT); //Potmeter pin

  //Load cell
  scale.set_scale(22290);  //Calibration Factor obtained from first sketch
  scale.tare();             //Reset the scale to 0

  //Accelerometer
  OpenLog.println("Test accelerator");
  if (! lis.begin(0x18)) {
    OpenLog.println("Couldn’t start");
    while (1) yield();
  }
  // lis.setRange(LIS3DH_RANGE_4_G);   // 2, 4, 8 or 16 G!
  OpenLog.print("Range = "); OpenLog.print(2 << lis.getRange()); //Range is 2G by default
  OpenLog.println("G");

  //BPM
  // Configure the PulseSensor object, by assigning our variables to it.
  pulseSensor.analogInput(PulseWire);
```

```
  //pulseSensor.blinkOnPulse(LED13);       //auto-magically blink Arduino’s LED with heartbeat.
  pulseSensor.setThreshold(Threshold);

  // Double-check the "pulseSensor" object was created and "began" seeing a signal.
  if (pulseSensor.begin()) {
    OpenLog.println("We created a pulseSensor Object!");  //This prints one time at Arduino power-up,  or on Arduino reset.
  }

  OpenLog.print("\n");
  OpenLog.println("potLevel,upperPulse,load(kg),storeLoad,filtLoad,BPM,filteredBPM,dutyCycleValue,motorActivation,time,accX,accY,accZ");

}


void loop() {

// Potmeter and upper sensitivity value
  valuePot = analogRead(potPin); //read potmeter value, will be a value between 0 and 1023
  maxPulseFromPotmeter(valuePot, upperPulse, potLevel); //takes in value from potmeter to adjust how high max pulse is
  OpenLog.print(potLevel); OpenLog.print(","); //prints level potmeter is on - 0,1,2,3
  OpenLog.print(upperPulse); OpenLog.print(","); //prints upper pulse value

//Load cell
  load = scale.get_units();
  OpenLog.print(load, 3);  //prints load up to 3 decimal points
  OpenLog.print(",");
  OpenLog.print(storeLoad); OpenLog.print(","); //prints the previous load value
  noiseFilterLoad = load - storeLoad;
  if (abs(noiseFilterLoad) >= 15) {load = storeLoad;}
  filteredLoad = smoothingConstLoad*load + (1-smoothingConstLoad)*filteredLoad;
  OpenLog.print(filteredLoad); OpenLog.print(","); //prints filtered load value
  storeLoad = load;

//BPM and motor input
  int myBPM = pulseSensor.getBeatsPerMinute(); //stores BPM in variable
  OpenLog.print(myBPM); OpenLog.print(","); //prints BPM

  filteredBPM = smoothingConstBPM*myBPM + (1-smoothingConstBPM)*filteredBPM;
  OpenLog.print(filteredBPM); OpenLog.print(","); //prints filtered BPM value
  dutyCycleValue = map(filteredBPM, 60, upperPulse, 40, 210); //map dutyCycleValue after filteredBPM. Now max dutyCycleValue is 210. Max throttle input 40-220.
  dutyCycleBoundaries(dutyCycleValue); //makes sure dutyCycleValue stays between 0 and 210
  OpenLog.print(dutyCycleValue, 3); OpenLog.print(","); //prints duty cycle value


if (filteredLoad >= 2.0) {
  OpenLog.print("1"); //motor gets input
```

```
  OpenLog.print(",");
  analogWrite(motorPin, dutyCycleValue); //input to motor
}
else {
  dutyCycleValue = 0; //motor does not get input
  analogWrite(motorPin, dutyCycleValue);
  OpenLog.print("0"); OpenLog.print(",");
}

// Accelerometer (IMU)
  lis.read();      //get X Y and Z data at once (check if this is actually needed)
  sensors_event_t event;  //create a new sensor event to get normalized
    acceleration data
  lis.getEvent(&event);

  myTime = millis();  //prints time since program started
  OpenLog.print(myTime/milliToSec, 2); OpenLog.print(","); //prints time

  // Display the results (acceleration is measured in m/s^2)
  OpenLog.print(event.acceleration.x); OpenLog.print(",");
  OpenLog.print(event.acceleration.y); OpenLog.print(",");
  OpenLog.println(event.acceleration.z);

delay(5);

}
```

A.0.6 Code for ECG motor control concept

```
 /* Load cell with HX711 amplifier with Voltage output in PWM to be read by motor.

Load cell Amplifier to Arduino pins:
 2 -> HX711 CLK (white), change to 9
 3 -> DOUT (yellow), change to 10
 5V -> VCC
 GND -> GND

Potmeter pin
 A0 --> Analog Output
 5V --> +
 GND --> -

Accelerometer (IMU):
 SDA to pin A4 (blue)
 SDL to pin A5 (orange stripe)
 Vin to 5V (green)
 Gnd to GND (orange)

SD-card
 RXI of OpenLog to pin 5 on Arduino
 VCC to 5V
 GND to GND

```

```
Output pins
 6 --> PWM output to motor

*/

//Load cell
#include "HX711.h"
#define DOUT  10
#define CLK  9
HX711 scale(DOUT, CLK);
double calibration_factor {22290};
double load {0};
double filteredLoad {0};
const double smoothingConstLoad {0.1};
double noiseFilterLoad {0};
double storeLoad {0};

//Potmeter
#define potPin A0
int valuePot {0};
int potLevel {0};

//Accelerometer:
#include <Wire.h>
#include <SPI.h>
#include <Adafruit_LIS3DH.h>
#include <Adafruit_Sensor.h>
#define LIS3DH_CLK A5
#define LIS3DH_MOSI A4
Adafruit_LIS3DH lis = Adafruit_LIS3DH();

//SD-card
#include <SoftwareSerial.h>
SoftwareSerial OpenLog(0, 5); // 0 = Soft RX pin (not used), 5 = Soft TX pin

//ECG:
#include <eHealth.h>
float threshold = 2.7;
boolean belowThreshold = true;
float beat_new = 0;
float beat_old = 0;
float diff = 0;
float noiseTest = 0;
float newBPM = 70;
float newBPMStored = 70;
float oldBPM = 70;
float filteredBPM = 70;
float smoothingConstBPM = 0.15;
double dutyCycleValue{0};

//Motor input
#define motorPin 6

//UPPERPULSE VALUE
```

```
int upperPulse{270}; //This was changed to 200 for level 2

//Functions
void dutyCycleBoundaries (double &dutyCycle) { //Boundaries on duty cycle value
   if (dutyCycle < 0) {
    dutyCycle = 0;
  }
  if (dutyCycle > 210) { //Max is 210
    dutyCycle = 210;
  }
}

void setup() {
  //SD-card
  OpenLog.begin(9600); //Open software serial port at 9600bps

  //Load cell
  scale.set_scale(22290);  //Calibration Factor obtained from first sketch
  scale.tare();             //Reset the scale to 0

  //BPM
  OpenLog.print("\n");
  OpenLog.println("upperPulse,load(kg),storeLoad,filtLoad,time,ECG(V),newBPMStored,
    newBPM,filteredBPM,dutyCycleValue,motorActivation");
}


void loop() {

// Upper sensitivity value
  OpenLog.print(upperPulse); OpenLog.print(","); //prints upper pulse value

//Load cell
  load = scale.get_units();
  OpenLog.print(load, 3);  //prints load up to 3 decimal points
  OpenLog.print(",");
  OpenLog.print(storeLoad); OpenLog.print(","); //prints the previous load value
  noiseFilterLoad = load - storeLoad;
  if (abs(noiseFilterLoad) >= 15) {load = storeLoad;}
  filteredLoad = smoothingConstLoad*load + (1-smoothingConstLoad)*filteredLoad;
  OpenLog.print(filteredLoad); OpenLog.print(","); //prints filtered load value
  storeLoad = load;

//BPM and motor input
  float t = millis();
  OpenLog.print(t/1000); OpenLog.print(",");

  float ECG = eHealth.getECG();
  OpenLog.print(ECG, 1); OpenLog.print(",");

  OpenLog.print(newBPMStored); OpenLog.print(",");
  OpenLog.print(newBPM); OpenLog.print(",");
  OpenLog.print(filteredBPM); OpenLog.print(",");

```

```
  dutyCycleValue = map(filteredBPM, 60, upperPulse, 40, 220); //map dutyCycleValue after filteredBPM. Now max dutyCycleValue is 220. Max throttle input 40-220.
  dutyCycleBoundaries(dutyCycleValue); //makes sure dutyCycleValue stays between 0 and 220
  OpenLog.print(dutyCycleValue, 3); OpenLog.print(","); //prints duty cycle value

if (ECG > threshold && belowThreshold == true) {
  diff = t - beat_old;    // find the time between the last two beats
  newBPM = 60000 / diff;    // convert to beats per minute
  newBPMStored = newBPM;
  belowThreshold = false;
  noiseTest = newBPM - oldBPM;
  if (newBPM < 60) {newBPM = oldBPM;}
  filteredBPM = smoothingConstBPM*newBPM + (1-smoothingConstBPM)*filteredBPM;
  beat_old = t;
  oldBPM = newBPM;
}
  else if(ECG < threshold) {
      belowThreshold = true;
}

if (filteredLoad >= 2.0) {
  OpenLog.print("1"); //motor gets input
  analogWrite(motorPin, dutyCycleValue); //input to motor
}
else {
  dutyCycleValue = 0; //motor does not get input
  analogWrite(motorPin, dutyCycleValue);
  OpenLog.print("0"); //OpenLog.print(",");
}

OpenLog.print("\n");
delay(5);

}
```

A.0.7 Code for calibration of load cell

```
#include "HX711.h"  //You must have this library in your arduino library folder

#define DOUT  3
#define CLK  2

HX711 scale(DOUT, CLK);

//Change this calibration factor as per your load cell once it is found you many need to vary it in thousands
float calibration_factor = -22290; //-106600 worked for my 40Kg max scale setup

void setup() {
  Serial.begin(4800);
  Serial.println("HX711 Calibration");
  Serial.println("Remove all weight from scale");
```

```
  Serial.println("After readings begin, place known weight on scale");
  Serial.println("Press a,s,d,f to increase calibration factor by 10,100,1000,10000
     respectively");
  Serial.println("Press z,x,c,v to decrease calibration factor by 10,100,1000,10000
     respectively");
  Serial.println("Press t for tare");
  scale.set_scale();
  scale.tare(); //Reset the scale to 0

  long zero_factor = scale.read_average(); //Get a baseline reading
  Serial.print("Zero factor: "); //This can be used to remove the need to tare the
    scale. Useful in permanent scale projects.
  Serial.println(zero_factor);
}

void loop() {

  scale.set_scale(calibration_factor); //Adjust to this calibration factor

  Serial.print("Reading: ");
  Serial.print(scale.get_units(), 3);
  Serial.print(" kg"); //Change this to kg and re-adjust the calibration factor if
    you follow SI units like a sane person
  Serial.print(" calibration_factor: ");
  Serial.print(calibration_factor);
  Serial.println();

  if(Serial.available())
  {
    char temp = Serial.read();
    if(temp == '+' || temp == 'a')
      calibration_factor += 10;
    else if(temp == '-' || temp == 'z')
      calibration_factor -= 10;
    else if(temp == 's')
      calibration_factor += 100;
    else if(temp == 'x')
      calibration_factor -= 100;
    else if(temp == 'd')
      calibration_factor += 1000;
    else if(temp == 'c')
      calibration_factor -= 1000;
    else if(temp == 'f')
      calibration_factor += 10000;
    else if(temp == 'v')
      calibration_factor -= 10000;
    else if(temp == 't')
      scale.tare();  //Reset the scale to zero
  }
}
```

Appendix B

Project thesis

NTNU
Kunnskap for en bedre verden

TKT4550 Stuctural Engineering

Pre-Master Thesis

Dina Zimmermann

Department of Structural Engineering

September 2021

I Abstract

This project seeks to investigate a way of implementing different sitting positions and incorporating a turning mechanism in a propulsion-assisted cross-country sit-ski prototype, continuing Aase and Forr's master's thesis. The purpose of this is to make the product flexible and applicable for the users. This assistive sports equipment is important for getting disabled individuals with varying physical activity levels out moving and enjoying the outdoors in the wintertime. However, the previous prototype was limited to one sitting position, and it had no means of turning, which limited the product to users with extensive trunk muscle control.

Two interviews were conducted to get a deeper insight into the users and their needs. Subsequently, two wooden prototypes were built using the principles of prototyping. The first prototype was inspired by the sit-ski from the former master thesis. This proved to incorporate all the wanted sitting positions but was too small to fit an average male. Secondly, a larger prototype with more features such as feet- and leg rests were built. A turning mechanism was investigated by switching from two to four skis and mounting a skateboard truck to the front and back of the sit-ski.

It was found possible to incorporate all four main sitting positions in cross-country sit-ski in the final prototype. This means that the possible product may fit many users and cease the need of buying a new sit-ski if one wants or needs to change the sitting position. Future research should commercialize the prototype by investigating suitable materials and figuring out a suitable production line.

II Sammendrag

Dette prosjektet ønsker å undersøke en måte å implementere ulike sittestillinger og implementere en svinge-mekanisme i en fremdriftsassistert skipiggekjelke-prototype, som en fortsettelse av Aase og Forrs masteroppgave. Hensikten med dette er å gjøre produktet fleksibelt og anvendelig for brukerne. Dette sportshjelpeutstyret er viktig for å få funksjonsnedsatte personer med varierende fysisk aktivitetsnivå i bevegelse utendørs. Imidlertid var den forrige prototypen begrenset til én sittestilling og den hadde ingen mulighet for å svinge kjelken, som begrenset produktet til brukere med stor magemuskelkontroll.

For å få en dypere innsikt i brukerne og deres behov ble det gjennomført to intervjuer. Deretter ble to prototyper av tre bygget etter prinsippene for prototyping. Den første prototypen var inspirert av skipiggekjelke-prototypen til den tidligere masteroppgaven. Denne viste seg å inkludere alle de ønskede sittestillingene, men var for liten til å passe en gjennomsnittlig mann. Deretter ble det bygget en større prototype med flere funksjoner som fot- og benstøtter. En svingmekanisme ble undersøkt ved å bytte fra to til fire ski og montere en skateboardtruck foran og bak på kjelken.

Det ble funnet mulig å realisere alle fire hoved-sittestillingene i den endelige skipiggekjelke-prototypen. Dette betyr at produktet vil kunne passe mange brukere og at de kan slippe å kjøpe en ny kjelke dersom de ønsker å endre sittestilling. Fremtidig forskning bør fokusere på kommersialisering av prototypen ved å undersøke materialer og finne en passende produksjonslinje.

III Preface

The base of this specialization project was to develop Aase and Forrs master's thesis further. This is a collaboration with Henrik Krogh Stabell, but we are writing individual specialization theses. We divided our project into focus areas. I will focus on the sitting positions, and Stabell will focus on the belt and motor system. Together we conducted interviews and worked work on the turning aspect of the sit-ski.

I want to show gratitude to SIAT (Senter for Idrettsanlegg og Teknologi), Exero Technologies, and Elsykkelbutikken for their support.

NTNU, Trondheim 20.12.2021

Dina Zimmermann

Table of Contents

1 Introduction

The cross-country trails in Norway are steep and curved, making them inaccessible to cross-country sit-skiers. A sit-skier uses a sled, due to leg impairments, connected to a pair of classic skis and generates propulsion by poling [9]. It is harder to generate force using only the upper body. Inevitably, uphill poling is challenging. Downhill slopes can also cause difficulties. If the slope is curvy, steep, or long, the sit-skier can lose control and fall. In an ideal world the trails would be facilitated for sit-skiers, but this will not happen any time soon. So, how can cross-country trails become available for sit-skiers?

To face these challenges, the *equipment* needs to be improved. A sit-ski is an assistive technology, which is defined as ”any product, instrument, equipment, or technology adapted or specially designed for improving functioning of a disabled person” [7]. Developing assistive technology can be a big challenge [5]. The number of users is limited, and the users have unique and specific needs. In addition, low manufacturing quantity and individualization of the equipment can lead to higher costs. These reasons might explain why today's market does not offer any sit-skis with propulsion assistance. The majority of them also lack a functioning steering system.

1.1 What is cross country sit-ski?

Cross-country sit-ski (CCSS) is one of the sport classes in the Winter Paralympic Games [13]. In these competitions, the challenges described in the introduction are taken into account using courses specifically designed for sit-skiers. The World Para Homologation Guide specifies that these courses cannot have any steep hills, with a gradient $> 12\%$, that they should have straight run-outs after a downhill slope, and that corners should be placed where speed is slow [18]. In a 3 km course, the maximum climb is 15 meters for sit-skiers, compared to 65 m for regular cross-country athletes [8]. Further, to ensure fair competition, the sit-skiers are classified into five categories based on their trunk control: LW10, LW10.5, LW11, LW11.5, LW12 [6]. The ability to extend and flex the trunk determines how large momentum is transferred to the poles and therefore has a large impact on the propulsion generation [11]. Class LW10-athletes have limited trunk muscle control to the point where they would not be able sit without support of the upper body. Class LW12-athletes, on the other hand, have normal trunk control.

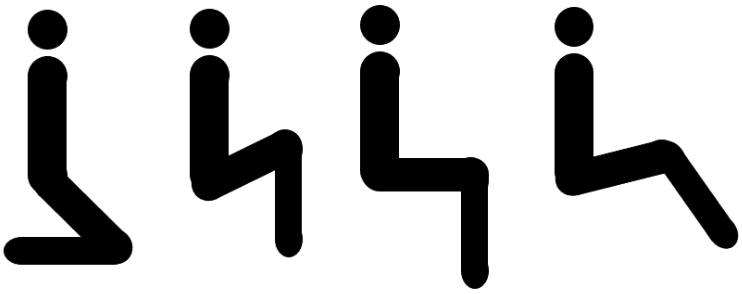


Figure 1: Main sit-ski sitting positions: KL, KH, KN, and KLS

The level of impairment affects the sitting postures of the sit-skiers [9]. Figure 1 displays the four main types of sitting positions: knees lower than hips (KL), knees higher than hips (KH), knees neutral to hips (KN), and legs stretched (KLS) [1]. LW10 athletes have a KH sitting position to support the trunk while skiing, while athletes with more substantial trunk control usually prefer a KL position [13]. The latter provides a more extensive range of motion and can therefore generate larger poling forces. Karczewska-Lindinger's study on force generation of Para-Nordic sit-skiers showed that the LW12-athletes, with a KL sitting position, produced a higher maximum speed compared to LW10-11-athletes [11].

However, sit-skiing for recreational purposes is different. The sit-ski that will be developed in this project is intended to be used as a leisure time activity. Therefore, the maximum speed is not necessarily the most crucial aspect of the sport. In contrast, the focus should be on having a good experience and being comfortable.

1.2 The previous master thesis

The base of this project is Forr and Aase's master thesis. In order to improve the assistive technology available for sit-skiers today, Aase and Forr built a propulsion assisted prototype of a cross country sit-ski, see Figure 2. The drive system consists of a belt with an electrical bicycle hub-motor powered by a bicycle battery provided by Elsykkelbutikken [1]. The motor is activated by a throttle attached to the ski poles, which is connected to the motor by a wire. Linear actuators are used to move the belt up and down, and braking can be performed using the mechanical brake between the legs. By implementing this system, the users were suddenly able to conquer a steep alpine slope with a gradient of 23%. These results are great when comparing it to the maximum gradient of 12% in Paralympic courses [18]. The testing also found that the belt had resistance and worked as a downhill brake.

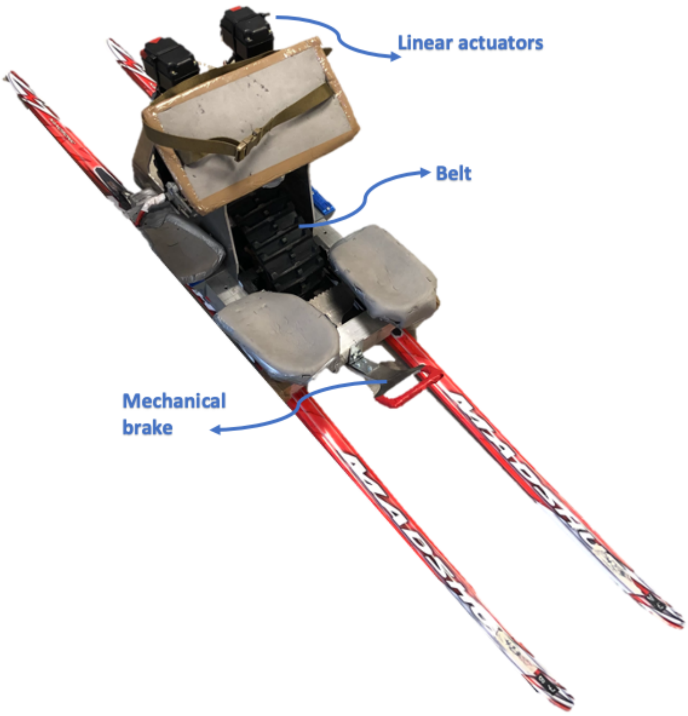


Figure 2: Previous prototype developed by Aase and Forr

The prototype has a KL sitting position, but Forr and Aase states: ”It is possible to adjust the seat to all the main sitting positions (KL, KH, KN, and KLS) and allow for better personalization” [1]. The seat of the prototype can switch angles to fit all four main sitting positions. However, there is nowhere to place the legs if one would want another sitting position. In addition, the linear actuators blocked the adjustment of the seat, so it was not possible to use the belt while sitting in another sitting position. The ”Conclusion and Further Work” section of their thesis says:

”Facilitating all four sitting positions will be beneficial to include a wider range of users”.

Further, the prototype could not turn. It is connected to a pair of classic skies, as most sit-skis on the market are. To turn on Aase and Forr’s prototype, one must use the poles to push the sled in another direction. This is a reoccurring problem in the sport, as some athletes develop their own turn technique. One technique is to use the whole body to jump and change the direction of the sit-ski. Amateurs should not be expected to use such a technique. The extensive use of arms for turning can be difficult if the user only has one functioning arm or the curve is too sharp. As it is a wish to offer the sit-ski to the broadest possible audience, this is not optimal.

1.3 Exero Technologies

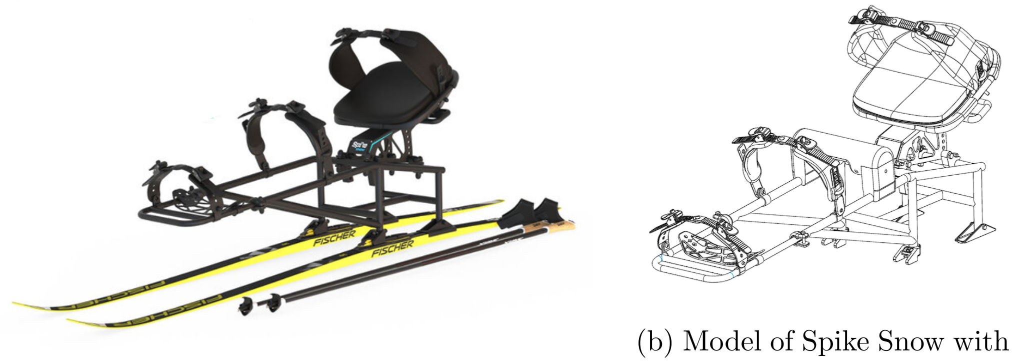
A collaboration with Exero Technologies was initiated. Exero Technologies is a start-up company that develops assistive technology, specifically sports equipment. Spike is Exero Technologies’ first product. It is a summer-based activity aid that makes it possible to train sit-skiing in the year’s warmer months. The company offers Spike with two different sitting positions: one with KL, see figure 3a, and one with KLS, see figure 3b.

(a) Spike with KL sitting position

(b) Spike with KLS sitting position

Figure 3: Spike

Further, Exero has a winter-based product. This is called Spike Snow, see Figure 4a, and is a cross country sit-ski with a KLS sitting position. This sit-ski has straps that hold the legs together. In addition, it has a mountable leg support as seen in Figure 4b. This support is additively manufactured and can be mounted on under the leg strap as support for the thighs.



(a) Spike Snow

(b) Model of Spike Snow with leg support

Figure 4: Spike Snow

1.4 Aim of this project

The aim of this project is improve some of the challenges from the previous master thesis. The focus is on two selected areas. The first is to investigating the possibility of including all four sitting positions in a sit-ski. The second is to explore a way of incorporating a steering system. The main goal of the final master thesis is to get a propulsion-assisted product on the market and thereby make it available for sit-ski users.

1.5 Structure of the thesis

The structure of this thesis is in chronological order. The reasoning is that it coincides nicely with the prototyping process. The nature of this process is to build a prototype and learn from it. Consequently, it is reasonable to explain what was learned and argue the choices that were made to build the next. The main body of the thesis is divided into five sections. The first section is called ”Development theory” and is about what approaches were taken under the development and design. The next section is ”User interviews”, where two sit-skiers were interviewed to understand the user needs better. ”The steering system”-section discloses an implementation of a functioning steering system. Lastly, the prototypes are presented: ”The first prototype” and ”The second prototype”. The method, results, and discussion are incorporated in the running text of these sections. To conclude, the section ”Conclusion and further work” sums up the thesis.

2 Development theory

The development approach for this thesis was prototyping. What is a prototype, or more importantly - what is the *value* of prototyping? Zimmermann has written the following: ”Ulrich and Eppinger [17] describes a prototype like this: ”an approximation of the product along one or more dimensions of interest”. This is a definition that is open – a prototype can be so many different things. It does not even have to be a physical thing. This definition only demands that the entity must explore an aspect of interest to the designer in regards of the product. A definition from the field of Computer Human Interaction is: ”Prototypes are the means by which designers organically and evolutionary learn, discover, generate, and refine designs” [15]. This definition is even more vague about what the prototype is, but rather focuses on what the prototype is supposed to *do*. It is a tool to help the designer. In both definitions prototypes are looked at as a means of learning. In Ulrich and Eppinger’s definition the designer explores a dimension of interest in order to gain more information about this dimension. In the second definition the designer uses the prototype to explore and learn about the design.

Now that we have looked at some definitions of what a prototype can be, let’s look at what prototyping is. Ulrich and Eppinger [17] explained it simply: ”Prototyping is the process of developing such an approximation of the product”. In other words, prototyping is making prototypes. In Human Computer Interaction, the verb is explained like this: ”Prototyping is an activity with the purpose of creating a manifestation that, in its simplest form, filters the qualities in which designers are interested, without distorting the understanding of the whole” [15]. Here prototyping is not only making a prototype, but about making a purposeful prototype. This means that you must think about what the prototype is supposed to represent and the possibilities and limitations it has.

So, what is the value of prototypes and prototyping? To understand the value of prototyping, we must investigate different dimensions prototypes can move into. Houde and Hill [10] has a model of what prototypes prototype, and this can give us a deeper understanding of the value of prototyping. Figure 5 shows a picture of the model. There are three dimensions which represent a class of questions in design: *role*, *look and feel* and *implementation*.

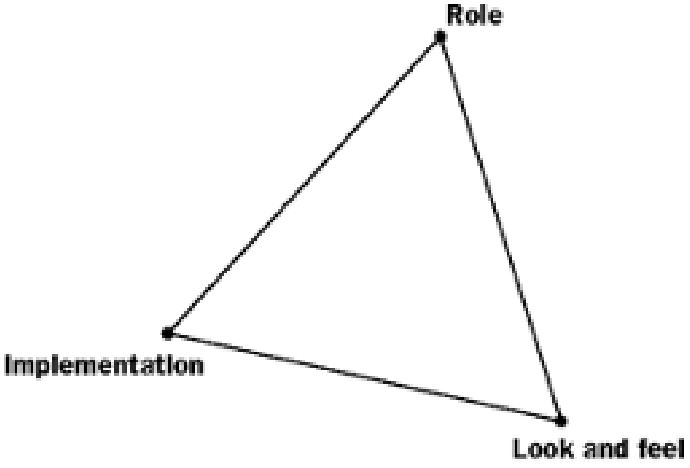


Figure 5: Model of what prototypes prototype

This means that prototypes can help us answer questions about role, look and feel and implementation. When focusing on the role prototype, it can answer questions about the functionality. The look and feel prototypes can give people a sense of what the product might be. Implementation prototypes can make us learn about the technical challenges and get a sense of the performance of the prototype, which is helpful in a design process. We must evaluate what questions we want to answer and what we don't, and this makes prototyping a valuable tool.

Prototyping makes it easier to communicate. Have you ever tried to explain an idea to a friend, and they have ended up looking confused? This could probably be avoided if you had a prototype. Role prototypes can be used to communicate to your design team what the main function of the final product might be. Look and feel prototypes can be used to communicate with potential users to get their feedback on its façade. Implementation prototypes can communicate a technical detail to your engineering colleague. "Prototypes are more than engineered objects for iterative testing; they are communication tools" [14]. This aspect shows how prototypes are valuable communication tools.

Further, prototyping can get you out of your head and into action. Sometimes thinking about a problem can make it seem more complicated than it is. You have probably also experienced feeling stuck in a design challenge and it is limited how long you can dwell on a problem to fix it. If you want to make a physical prototype, you have to build something and this demands action.

To conclude, prototyping can help us think about what design questions we want to answer. Do we want to explore the functionality, the façade or the technical features? The prototype can provide us with information in all these dimensions of the design challenge. Thinking about the purpose of the prototype can give us clarity on what we want to achieve. Once we know the purpose, we can start making the prototype. Prototyping encourage action because you can't make a prototype without acting. Once we have our prototype it can facilitate communication, either with our colleagues, stakeholders, users or leaders." Again, prototypes are a means of exploring and learning, which is their primary function in this thesis.

Moreover, user interviews were conducted to understand the users' needs better. Needs finding is denoted as "a qualitative research approach to studying people to identify their unmet needs" [16]. Patnaik [16] argues that needs are stronger than any solution, and therefore it is important to find the needs of the user. As an example, he says that floppy disks are not a competitive solution anymore, but the need to store computational data is still of current interest. Further, more possibilities are held open by focusing on the needs instead of a particular solution. In this way, it is possible to avoid premature decision-making.

In many design cases, the designers have an idea of the user's needs based on their own experiences. When designing for disabled users, however, it can be hard to understand what it entails to live with limited functionality [2]. Due to this reason, understanding the needs of users with disabilities and trying to put yourself in their shoes can be even more critical. Assistive technology plays an essential part in the independence of their users [3]. As a designer, it is crucial to understand the issues that can arise during the use of the equipment. Bühler says: "The user involvement in every step of the development procedure is meaningful" [3]. This project is not in the beginning phase anymore, but as Bühler states, it is still important to involve users.

Moreover, Choi [5] points out that developing assistive technology can be complex since the users have a variety of disabilities. He argues that these can vary ”from those with slight to moderate disabilities who may have more general needs to those with more severe disabilities who may have very unique and specific needs” [5]. This can make it hard to end up with one solution that fits many users. It is possible to learn more about who the users are through conversation. The following section conveys what the users had to say.

3 User interviews

To gain further knowledge about the user group, two individuals were interviewed. The first interview object has a high spinal cord injury that results in low trunk control. She uses a KH sitting position and sits in a scull seat. The seat is a carbon fiber shell that has been custom-made to fit her body. The shell reaches over the chest to ensure support. The downside with carbon is that it does not insulate well, making it cold. Therefore, she has to bring a hot water bottle and warm clothes. The interview object stressed that it would be important to focus on the user groups that do not function independently on a day-to-day basis. A product like the one being developed would mean so much to these users. As a person who needs assistance round the clock, it is hard to get a sense of freedom. When the interviewee sits-skis, she is dragged by a skier in front of her. The trip does not become the same nature experience as if she was on her own in the tracks. Lastly, she has limited grip strength. To attach the pole to her hand, she would tape them together. This fact would make the throttle solution of the previous master-thesis an unusable solution.

The second interview object had been sit-skiing for several years. He has Cerebral Palsy (CP), described as ”a static neurologic condition resulting from brain injury that occurs before cerebral development is complete” [12]. Patients with CP can experience spasms, as 70-80 % of the patients have these clinical features [12]. The spasms can bring a sit-skier out of balance, but the interviewee said that how the spasms act out is individual. The interview object said that he did not have many spasms in the upper body, so he was not bothered by them while sit-skiing. The throttle solution could lead to difficulties for someone with hand-spasms. It would be unfortunate to propel the sit-ski without warning due to this. Equally important, the interview object told that fine movements could be challenging, such as pushing a button. These are things to keep in mind while developing the sit-ski.

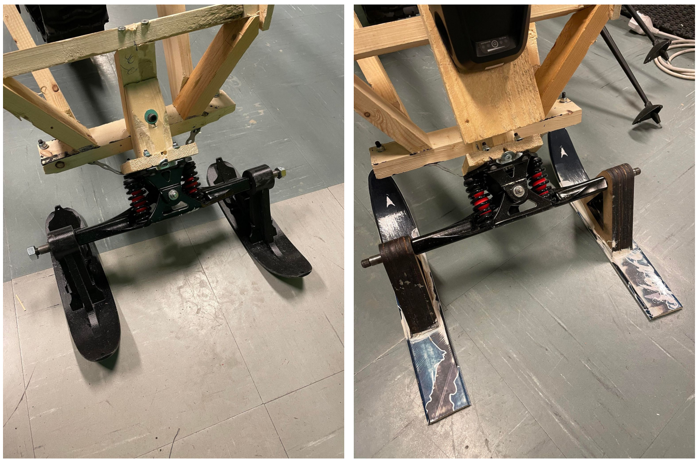
Furthermore, the interview object told us that he started using a sit-ski with a KLS-sitting position. This sit-ski was a good starting point, but it was hard to generate propulsion due to the sitting position. The sit-ski also lacked a brake, making it frightening to ski downhill. Skiers often ruin the tracks in downhill slopes throughout the day, and it is hard to keep the balance outside the tracks. The interview object said that he would use his poles considerably to compensate for the lack of balance. The imbalance would make him fall at times.

After a few years, the interview object switched to a sit-ski with KL sitting position. The change of sit-ski might not have been necessary if the sit-ski had included multiple sitting positions. With this sit-ski, he was able to generate more force. He said that he could get muscle soreness from sitting on his knees. The sit-ski has a break, but the interviewee is reluctant to use it since it might ruin the tracks. This concern could be a challenge regarding the belt, as it will leave marks on the tracks.

As for transportation, this could get demanding to manage. The interviewee's first sit-ski was a bit bigger, which made it more difficult to transport. The interview object usually went skiing with his family, who helped him with the logistics. Another challenge was to get in and out of the sit-ski. It could get unstable as the interview object would try to get in. Sometimes this could take multiple tries. All these points are helpful to have in the back of the mind while designing and developing the sit-ski prototype.

4 Steering system

As previously mentioned, most of the sit-skis on the market today do not have a functioning steering system. Aase and Forr's prototype did not have this either. Exero Technology's summer sports equipment, Spike, has a turning mechanism that makes it possible to steer the sled by shifting the weight to either side. The mechanism is implemented by using a particular type of skateboard truck called a channel truck [2]. The channel truck has a cushioning effect through springs with dampers on the inside. The trucks can be seen in Figure 6, where the spring surrounds a red plastic piece on either side of the midpoint.



(a) Front truck with additive manufactured skis (b) Back truck with normal skis

Figure 6: Channel trucks mounted with skis

To implement turning in the sit-ski, classic skies were changed into four individual skis. Exero provided the project with two channel trucks. The wheels were switched out with skis provided by SIAT. Figure 6 shows the setup of the different skis. The front skis was an additive manufactured pair, see Figure 6a. The back skis were a pair of regular skis with laser cut bindings attached with acryl, see Figure 6b.

A design challenge with the channel truck was that it was too wide to fit in a regular ski track. It is a wish to have the skis fit in regular ski tracks, as this provides additional balance. The dimensions of a standard ski track can be found in Figure 7. The distance between the skis is 26 cm. When building the next prototype,

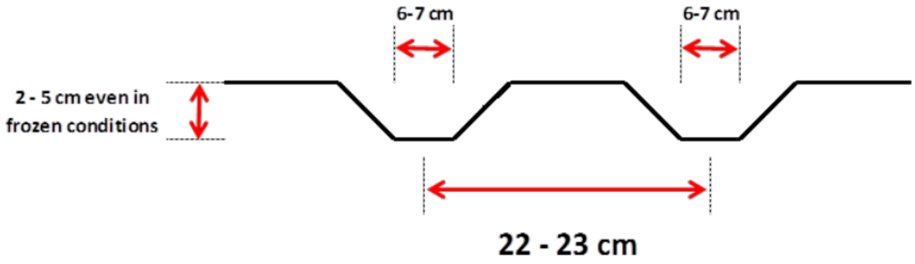


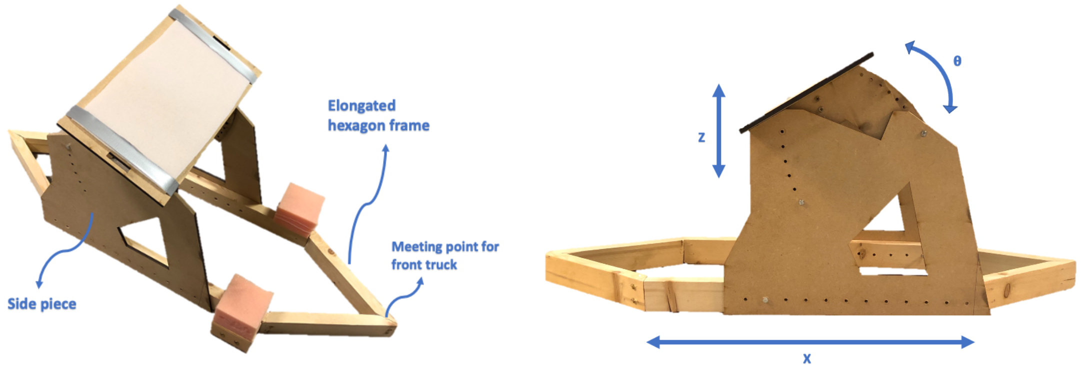
Figure 7: Dimension of ski tracks

this will have to be considered.

To test the turning concept further, the channel trucks were mounted on Stabell's prototype. The turning system was not assembled to the prototypes in this pre-master thesis. The main reason for this was to investigate the belt's impact on the turning. To read about the results, see Stabell's pre-master thesis.

5 The first prototype

The first prototype aimed to test the possibility of having all four sitting positions; KH, KL, KM and KLS, in the same sit-ski. The design was inspired by last year's master thesis, with the same seat rotation and size as the previous prototype. The primary material used to build the prototype was wood. The advantage of using wood is that it is easy to build with and relatively strong. This facilitates a quick way of building and testing the different sitting positions. A new design challenge with the propulsion-assisted sit-ski was to make space for the belt.



(a) Prototype parts

(b) Degrees of freedom

Figure 8: First prototype

Initially, the frame of the sit-ski was defined. An elongated hexagon shape was chosen to make space for the belt and have a natural meeting point where the trucks were supposed to be mounted onto the sit-ski, see Figure 8a. Following this, the side pieces of the seat were CADed and laser cut. The holes at the bottom of the side pieces made it possible to move it back and forth, consequently changing the point of gravity. This is denoted the horizontal degree of freedom X, as seen in Figure 8b. In addition, the seat could be rotated in order to change the sitting positions. This is illustrated in the rotational degree of freedom θ. Finally, the seat had a vertical degree of freedom denoted Z. To represent all the sitting positions, these degrees of freedom were chosen.

To test if the sitting positions would fit different human body sizes, the first prototype was tested on a male and female test subject. The test entailed that the test

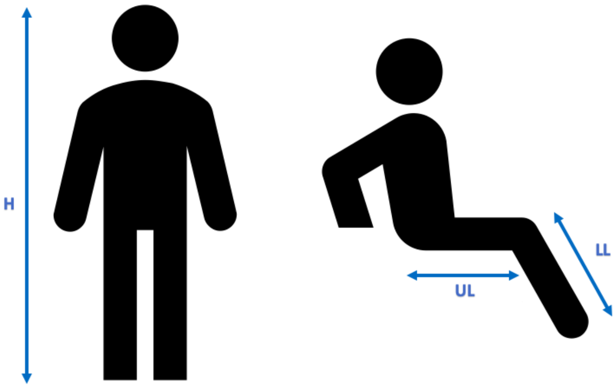


Figure 9: Height characteristics: height H, upper leg length UL and lower leg length LL.

Height characteristics			
	Height H [cm]	Lower leg LL [cm]	Upper leg UL [cm]
Female test subject	167	54	55
Male test subject	193	63	66

Table 1: Height characteristics of the test subjects

subject tried to sit in the four different sitting positions of the sit-ski prototype. Figure 9 display the height measurements that where taken, followed by the numerical values of the testers in Table 1. The average height of men in Norway is 178.9 cm and for women is 165.8 cm [4]. Since the male test subject was 193 cm, he was a good representation of a more extreme user in the context of his height. The female tester was higher than the average Norwegian woman, which is important to take into consideration when designing further.

It was quickly discovered that this prototype was too small to fit the male tester. In the KL sitting position, the male test subject's upper legs extended past the seat, causing his bottom to stick out. In the KN sitting position, the seat was not high enough to create a 90 degree angle. In the KH sitting position, the male test subject struggled to keep himself up. This seemed to be because the seat was underdimensioned, and there was no back support in the seat. Lastly, the legs of the male tester extended far past the end of the prototype in the KLS sitting position. The prototype fits the female test subject well. The testing showed that the next

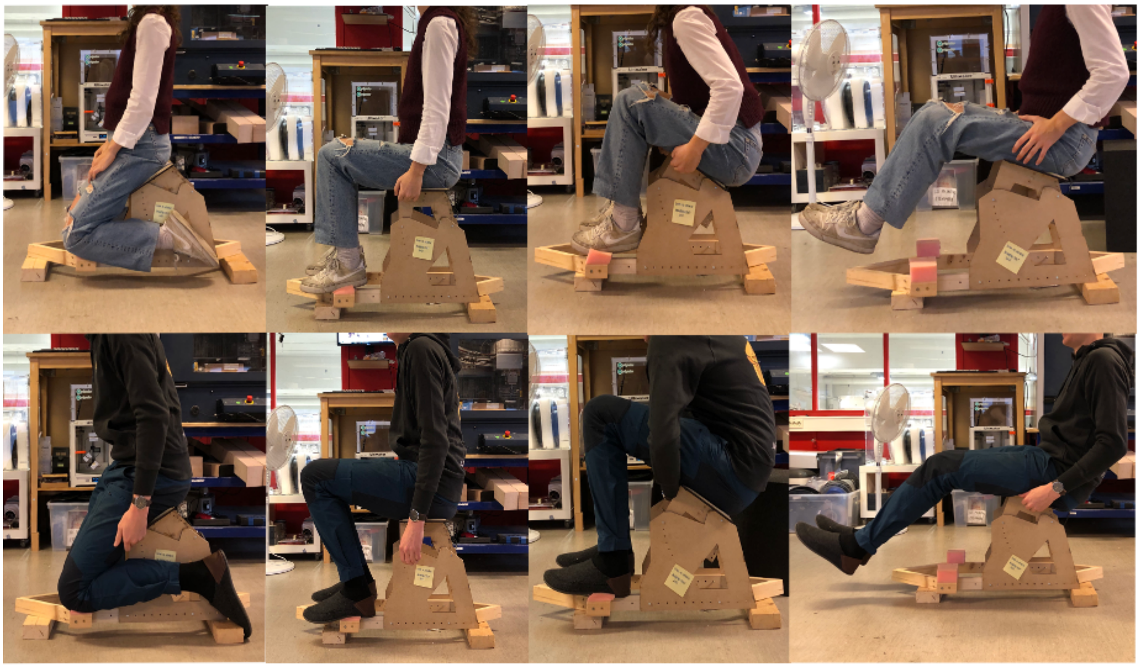
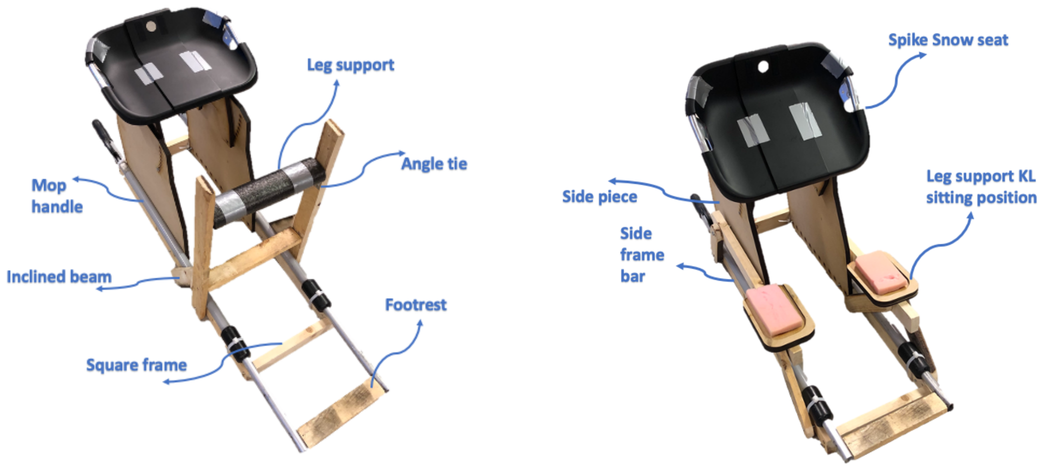


Figure 10: The first prototype tested by male and female test subject. From the left: KL, KN, KH and KLS.

prototype had to be built larger.

6 The second prototype

The second prototype is an iteration of the first prototype based on the experience gained from it. Firstly, the frame of the sit-ski was changed. Figure 11 shows the prototype with a KLS and KL sitting position. The elongated hexagon shape blocked the possibility of changing the side pieces in the horizontal direction X. Therefore, a square frame shape was chosen. To avoid the frame's shape to collide with the turning-mechanism of the skis, the frame and the truck have to be at different heights. This can be assured by mounting the trucks on the sit-ski at an angle. Next, new side pieces was CADed with the height characteristics of the male subject from Table 1 taken into account. Exero provided the project with a Spike Snow. The seat from this was disassembled to use in the second prototype.



(a) KLS sitting position

(b) KL sitting position

Figure 11: Second prototype

As presented in the Theory-section, Exero mounts additive manufactured leg supports onto the Spike Snow. With the new square frame, it would be easier to implement a similar solution to the prototype due to the equal length between the side frame bars, see Figure 11a. A leg support for the KH, KN, and KLS sitting positions was mounted onto the frame of the prototype. This was made out of wood, but could possibly be additive manufactured in the future. The leg support existed of two main columns connected by a transverse beam that was braced by angle ties. To brace the leg support in the X-direction, inclined beams was mounted onto each column.

The sit-ski prototype needed a place to rest the feet as this was lacking in the previous prototype. The footrest was made mobile in the X-direction to allow for length adjustment depending on the user's height characteristics. Two mops that had an extension possibility were disassembled so that only the mop handle was left. Further, they were mounted on top of the side frame bars. The mops were connected by a transverse beam where the feet should be placed.

For the KL sitting position, a place for the knees and the lower legs to rest on would have to be implemented. To take into account the different upper leg lengths and the different angles of the seat, the support should be able to move in the X- and Y-direction. The solution was the support construction shown in Figure 11b. The sloped beams allow for adjustment in X- and Y-direction. The knee pad was also moveable.

The testing followed the same procedure as the last prototype. How was the experi-

Figure 12: The second prototype tested by male and female test subject. From the left: KL, KN, KH and KLS.

ence of sitting in the four different sitting positions in the sit-ski prototype? Was it possible for both the male and female test subjects to sit on the prototype? Figure 12 shows the second prototype tested by the male and female test subject. The male test subject fit in the KL sitting position, in contrast to the first prototype. The KN sitting position was also improved in regards to the male test object. His legs have an angle of 90 degrees, compared to the first prototype where the angle was < 90 degrees. In the KH-sitting position, the female test subject sat relatively high over the ground. In this regard, it could be necessary to lower the seat. The KLS sitting position was a good fit for both test objects. The male said he could feel the edge of the seat thug into his thighs. An improvement would be to make the seat edge more rounded.

7 Conclusion and further work

This project aimed to investigate the possibility of having the four main sitting positions in the same sit-ski and examine a way to incorporate a functioning steering system. To do so, two prototypes were build and knowledge from these was gained. Incorporating KL, KN, KLS and KH in one sit-ski proved possible. A solution for a turning mechanism using channel trucks was presented but needs to be tested further. Further work should entail a discussion with Exero Technologies regarding the solutions presented in this thesis. It is valuable to get their feedback as they have considerable experience within their field. In addition, the solution for the sitting position should be incorporated with Stabell's solution for the suspension of the belt.

An important aspect to look into as further work is the motor speed control. As mentioned previously, the way of solving this in the last prototype was by using a thumb throttle. This was not considered an optimal solution after the user interviews due to the fact that one user experienced spasms and the other had limited grip strength. There has come up a few ideas regarding the motor speed control. One of them is to connect the user to a heart rate monitor and regulate the speed of the motor after the pulse. This way, the user can decide where they want their pulse to be throughout the workout and thereby assess if they want a slow, less intense workout or push the pulse to the limit. Another option would be to incorporate a pressure sensor in the pole. The sensor can measure how much force is used to pole and regulate the motor assistance accordingly. This way, the experience might feel more natural.

Finally, materials and manufacturing methods should be examined as the goal of the final master thesis is to commercialize this propulsion-assisted sit-ski prototype.

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