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Master's thesis

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Early Phase Development of a Motorized Cross-Country Sit-Ski - Assistive Equipment for Para Sport Exercise

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Preface

This is a Master's Thesis written by two students in the field of Mechanical Engineering – the final work of a M.Sc. in Engineering Design and Materials in the Department of Mechanical and Industrial Engineering (MTP) at the Norwegian University of Science and Technology (NTNU). The work was aimed to develop assistive equipment in cross-country (XC) skiing and was a collaboration by three students.

We would like to show our gratitude to our supervisor Knut Einar Aasland (MTP) and co-supervisor Jørgen Falck Erichsen (SIAT) for much appreciated support and advice through the work. Much aid was also received in terms of materials to be implemented in prototyping. The institute NTNU SIAT was always helpful supplying skis, other requested equipment and travels of interest. Kristoffer Stork at Elsykkelbutikken proved to be very helpful and sponsored two hub motors used in the prototypes. The department of MTP also covered expenses and provided facilities. We are also thankful for valuable time and conversations with the Norwegian National Team in Para Cross-Country Skiing.

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Abstract

Individuals with physical impairments are often in need of assistive equipment to use the ski trails and enjoy the outdoors. Cross-country sit-skiing (CCSS) was experienced to be so strenuous for the users that it constrains the prevalence of the activity.

To assist with propulsion, the potential of motorizing a CCSS to be used in the groomed ski trails was investigated. Destruction of the groomed tracks was in focus as the challenge of providing propulsion should preferably be solved without disturbing other users of the trail system. It was found that the snow conditions varied greatly, being a critical parameter affecting which drive system was beneficial.

The development approach was inspired by set-based concurrent engineering (SBCE), creating prototypes of different concepts solving the same function – to transmit motor power to the snow. Prototypes of low fidelity were produced from scratch implementing an electrical wheel hub motor. Drive systems with different types of wheels and a rubber track were produced and tested, indicating the concept has potential but need further development.

KEYWORDS: *Assistive Equipment, Cross-Country Skiing, Sit-ski, Product Development, Prototyping*

Sammendrag

Personer med fysisk funksjonsnedsettelse har ofte behov for hjelpemidler for å bruke skiløyper og nyte naturen. Staking i piggekjelke oppleves å være så anstrengende for brukerne at det begrenser utbredelsen av aktiviteten.

For å hjelpe til med fremdriften ble potensialet til en motorisert piggekjelke for bruk i preparerte skiløyper undersøkt. Ødeleggelse av de preparerte løypene ble tatt hensyn til, da utfordringen med å gi fremdrift helst bør løses uten å forstyrre andre brukere av skiløypene. Snøforholdene varierte veldig, noe som var en kritisk faktor som påvirket hvilket drivsystem som var mest gunstig.

Utviklingsmetoden var inspirert av "set-based concurrent engineering". I utviklingen ble det bygget prototyper av forskjellige konsepter som løste den samme funksjonen - å overføre motorkraften til snøen. Prototyper av lav oppløsning ble produsert fra scratch med implementering av en elektrisk navmotor. Ulike drivsystemer av hjul og gummibelte ble produsert og testet, noe som viste at konseptet har potensiale, men trenger mer utvikling.

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Acronyms

Skiing terms

CCSS	=	Cross-Country Sit-Ski(ing)
DP	=	Double-Poling
XC	=	Cross-Country (Skiing)
WC	=	World Cup

Mechatronics

CPU	=	Central Processing Unit
RAM	=	Random Access Memory
FSR	=	Force Sensitive Resistor
(BL)DC	=	(Brushless) Direct Current

Other Acronyms

MDF	=	Medium-Density Fiberboard
SBCE	=	Set-Based Concurrent Engineering
FBD	=	Free Body Diagram
MTB	=	Mountain Bike
NAV	=	Norwegian Labour and Welfare Administration
SIAT	=	Centre for Sport Facilities and Technology

Physical Parameters

W_d	=	Normal Force on Drive Wheel
F_d	=	Drawbar Pull
F_t	=	Tractive Force
F_e	=	Tractive Effort
R_c	=	Motion Resistance
F	=	Drive Force
T	=	Motor Torque
r	=	Drive Wheel Radius
τ	=	Shear Stress
σ	=	Normal Stress on Surface of Shearing
c	=	Cohesion
ϕ	=	Friction Angle
A	=	Contact Area Between Snow and Track or Tire
i	=	Slip
v	=	Velocity of Vehicle
ω	=	Angular Velocity
l	=	Length of Contact Area of Track
b	=	Width of Contact Area of Track
K	=	Shear Deformation Modulus
μ_t	=	Coefficient of Traction
α	=	Angle of Uphill Gradient

Chapter 1

Introduction

The master thesis is a continued work based on a pre-master conducted by three Mechanical Engineering students in the fall of 2019. The pre-master and master thesis are results of a product development project within the NTNU Department of Mechanical and Industrial Engineering in collaboration with SIAT, Centre for Sport Facilities and Technology. The subject was proposed by Olympiatoppen, an organization that is part of the Norwegian Olympic and Paralympic Committee and Confederation of Sports. The thesis aims to find, discuss and test concepts and solutions to user needs found in the pre-master and throughout this project. The results of this thesis should serve as a base and give guidelines for further work in the development of the product rather than presenting finite solutions.

The pre-master project of the fall of 2019 worked as a basis to the thesis where background research of the problem was conducted and user needs were found. The needs were found by direct contact with users and firsthand experience, in addition to communication with Olympiatoppen. To get the full understanding of the thesis and the problem, parts of the pre-master in Appendix B are referred to in the text and should be read. This helps the reader to get an overview of the problem and some terms used in the para skiing community.

1.1 Background

The thesis covers the subject of the development of assistive sports equipment and Paralympic sports equipment. The assistive sports equipment in question is the cross-country sit-ski used both by professionals and amateurs in Nordic skiing. CCSSs are under constant development with most of the development targeting professionals and competitive equipment. Due to limitations in the competitive part of the sport, the development is often limited to rigidness and lowering weight. The focus on the thesis is therefore not competitive equipment, but rather on equipment for training and fun. The proposed devices should enable exercise for amateurs and beginners, possibly aiding recruitment to the sport. More background of the sports and the equipment can be found in the introduction of the pre-master in Appendix B.

Development of assistive sports equipment meant for amateurs and beginners also fits a goal presented by the Norwegian government. The Norwegian government, through NAV, pursues a goal to increase the level of activity of the general population, and in particular, individuals with spinal injuries and other physical limitations. Activity for such individuals often requires the use of assistive equipment. Assistive aids and sports equipment are sponsored by NAV since activity has been found to increase the quality of life and emotional value. These aids and the activities they make available are proved to increase the user's sense of freedom in everyday life and improve their functional capacity. The thesis work aims to develop assistive sports equipment that encourages activity in individuals with physical limitations by contributing to an increased feeling of joy of the sport. Although the development was focused on amateur athletes and beginners the intended user group did not exclude professional athletes. The assistive CCSS could be beneficial for professional users and possibly be implemented in their training. [1]

Figure 1.1: An adjustable CCSS with brakes, Tessier's Eskaip. [2]

The considered user group for the product would be individuals with different impairments wanting to participate in the activity of Nordic skiing. Including both beginners and experienced users and no limitation in regards to the type of impairment, the user group is characterized by variation. The variation is caused by the individual needs and limitations where the needs are greatly influenced by the user's condition or impairment. User needs can be very individual and therefore challenging to understand as a designer. Using firsthand experiences will not always be sufficient and designers should collaborate with actual users when developing the equipment.

Direct contact and feedback from users were supposed to solve the challenge of understanding individual needs and managing the diverse user group. Due to the circumstances caused by the outbreak of COVID-19 however, the thesis had to be adjusted and contact with users was limited. The development and results are therefore solely based on firsthand testing and subjective experience where the authors have tried to place themselves in the position of expected users. The initial physical approach using prototypes and testing also had to be aided by calculation. It should be pointed out that testing with actual users was planned and should be conducted at the earliest convenience in future work.

1.1.1 Pre-Master

The gathering of information was conducted through a pre-master in the fall of 2019 concerning the thesis, as seen in Appendix B. This involved knowledge generation, getting to know rules and regulations in the sport and general theory. The information gathering was done by conversations and interviewing of users and extreme users in the form of professional athletes and their trainers. The extreme users were made available through Olympiatoppen with an invitation to attend a training camp with the national Paralympic ski team of Norway. A theoretical investigation was also conducted as well as attending trial days for new users organized by Hjelpemiddelsentralen and NAV to meet inexperienced new users and producers of similar equipment. For further understanding, firsthand experience with existing equipment was also used. One of the sit-skis can be seen in figure 1.2. The knowledge generation was a continuing process and was conducted throughout the entire project. This worked as a basis in the development process.

The research of the sport in the pre-master showed great variations in existing equipment. For professional users, equipment ranges from custom-made sit-skis made fully from carbon, cast to fit a specific user, to simple rigid constructions. The range of equipment for amateur athletes and inexperienced users was also quite wide. Some CCSS were made extremely adjustable, aimed to fit a wide user group while other sit-skis had easier constructions with limited possibility to adjust. The adjustment possibility and construction usually has a great impact on the weight and the price of the device. An example of a commercial sit-ski is shown in figure 1.1.

The investigation of the rules and regulations for competitive equipment showed the strictness of the device and how this limits new development. The rules and regulations are not as imminent in the development of professional equipment meant for training purposes where the main limitation is a fixed sitting position corresponding to the one used in competition. For amateur use there are very few limitations, still, the development of such equipment is usually focused on weight reduction.

A portion of the pre-master also explores the possibility to implement rotational skies to improve handling and turning of the sit-ski, a secondary problem not in focus in the thesis. A concept to solve this was investigated by building a prototype and testing by the authors, comparing it to the handling of existing equipment. The testing gave somewhat non-conclusive results that needed further investigation. An interview with an extreme user conducted at a later stage revealed the essence of using commercial skis, and the concept using four customized small skis was discarded.

Figure 1.2: A CCSS tested in use by the developers.

The most relevant part of the pre-master for this thesis was the exploration of challenges the users face with the existing equipment and their needs. The most noticeable problem for amateur users was found to be the fatiguing and exhausting nature of the activity leading to a need for assisted propulsion.

1.1.2 Observations

Being part of the knowledge gathering, the Para World Cup at Lillehammer was visited in December 2019 immediately after the pre-master was finalized. The purpose of the participation was to investigate the facilitation of the trails, the equipment and revealing challenges professional athletes face executing their sport. It was also an ambition to get insight into improvements of equipment, physical limitations for the skiers and reasons for the fallout of new users. This involved the athlete's initial encounter with the sport and the feeling of trying a CCSS for the first time. Thoughts on development of new equipment were also discussed and their opinion on a sit-ski with assistive propulsion.

The course used in competition for the sit-skiers was customized and flatter compared to the course of other para-athletes and a WC course used for able-bodied skiers. The sit-ski trail for the longest race distance was about 2500 meters and had a height difference of 11 meters with a total climb of 36 meters per round. Whereas the corresponding trail for standing para-athletes had a height difference of 35 meters and a total climb of 95 meters per round. The numbers are taken from the trail description of the courses used in Lillehammer and can be found in the appendix of the pre-master thesis. The course had groomed ski tracks making turns easier to handle. It was observed that users with lower injuries conducted some of the turns outside the track while contestants with higher injuries, such as spinal cord injury, remained in the track for the entire turn.

Part of the WC course was one main climb, while the rest of the trail was relatively flat. The uphill was approximately 10° and would not be considered a difficult obstacle for an able-bodied skier. All but a few of the competitors had little to no problem mastering the obstacle. It was however observed that some athletes struggled to maintain propulsion for the duration of the climb and needed some assistance. The gradient of the main climb can be seen in figure 1.3.

An interview of interest was conducted during the race with Anne Kroken, an experienced person and leader in the para community. According to a her, the main climb observed in the race was steeper than what is usual in competitions. The observations and information gained from Anne Kroken led to a belief that the exercise of CCSS is so strenuous that even professional athletes could struggle in hills which were small compared to Norwegian recreational trails. In the interview it was also pointed out that training equipment for competing athletes must be in an identical sitting position as of competitions.

Interviews with a coach and a professional athlete at a high level were also conducted as conversations at the WC event at Lillehammer. The main outcome of these conversations is presented below.

Interview with US Ski Team Coach

The coach of the American Para Nordic Ski Team was interviewed inside the team's room of leisure together with all equipment. The CCSSs of the team were customized carbon fiber frames cast to fit the individual athletes. Concerning the product development, the frames were cast in carbon immediately – a completely new model was made if the fit to the athlete was not perfect when tested. The cost of producing one sit-ski was approximately 14 000 USD; an expensive trial and error development if the first attempt did not fit perfectly.

The best male athletes could DP through conventional XC courses, but it would be very tiresome. In daily training sessions, the able-bodied coach would attend to push the athletes in the climbs. A motorized CCSS could be applicable for long sessions in hard ski trails also for the best athletes if the sitting position was constant. She also added that many users would probably want to try a motorized sit-ski only due to the value of the experience. One should not underestimate the joy of trying a new activity, especially for people with physical limitations who do not have the same possibilities. For amateurs, she stated that it would not be necessary with a rigid CCSS – movement might be more fun. A project goal was also proposed: to attract more users and make it fun.

Interview with Birgit Skarstein

An interview with the athlete and her ski tester was conducted at the National Team lunch after a race in Lillehammer. It was stated that the athlete's first experience with a sit-ski was very hard. She believed many rookies will not proceed to further use as the activity was extremely exhausting as a beginner. In her case, she still wanted to proceed with the activity as sports were an important part of her life. The athlete considered herself a particular stubborn individual, she was not an average person. It was also mentioned that for professional users, ski testing is executed by able-bodied helpers. Birgit also proposed the idea of making the motorized CCSS as an attachment providing propulsion like an outboard drive system, instead of a complete sit-ski with motor integrated.

It was pointed out the reason for and importance of using commercial and standardized skis. CCSS users face additional wear and tear on the skis compared to able-bodied users.

Figure 1.3: Birgit Skarstein double-poling the toughest climb in WC Lillehammer 2019.

Sitting in a CCSS while skiing in the groomed track, it will be difficult to avoid dirt and stones in the snow, while standing skiers can more easily lift one foot to spare the skis and avoid obstacles when they see them. A greater need for a customized and expensive product will also make it harder to begin with a new activity.

1.2 Objective

The thesis grew into a greater project early in the process. The vision and mission of the thesis should therefore be put in context with the overall goal.

Vision – Overall goal of the project:

The work of the project aims to make cross-country skiing more available and fun for people with physical limitations. The end product should make it easier to take part in the activity and facilitate being outdoors. The user group is not limited to amateurs but includes professional athletes by making more trails available for training purposes.

Project mission:

To develop a motorized sit-ski to make the activity less strenuous and assist the skier with propulsion in training sessions and recreational trips.

Thesis mission:

The thesis work aims to explore and develop concepts of a motorized sit-ski, converging to one main concept and developing a prototype to show proof of concept with a focus on the propulsion system. The prototype is intended to work as an inspiration to subsequent development of a comprehensive product.

Due to COVID-19, the development process was interrupted as the workshop closed during the building of a functional prototype, so the realization of the product was not completed. The prototype was supposed to be tested at the national para event of Ridderrennet to obtain user feedback. The event was also canceled.

1.3 Existing Solutions

Different existing solutions were both tried and investigated as a part of the pre-master and early in the master thesis. Some investigated equipment was used as inspiration in the idea generation and solutions were implemented in the concepts trying to solve the design challenges presented in chapter 4.

1.3.1 Cross-Country Sit-ski

As mentioned earlier in the chapter, a variety of CCSSs exist. The equipment used by professional athletes ranges from ultralight custom-built racing sit-skis to simple sit-skis constructed to minimize cost. Amateur equipment is often more adjustable with higher weight but serves a wider user group. Some information about CCSS and sitting positions can be read in Appendix B section 1.2.

CCSSs for use in competitions

(a) **(b)**

Figure 1.4: Two CCSSs for competition in WC.

	Advantages
+	Lightweight
+	Responsive handling and maneuverability
	Disadvantages
÷	Each CCSS only applicable to one athlete
÷	Expensive
÷	Not available to everyone. Favorable for the most professional national teams
÷	No braking system on the CCSS, relying on an experienced user

Table 1.1: Aspects of CCSSs designed for competing elite athletes.

Commercial CCSSs

	Advantages
+	Often high degree of adjustability of sitting position etc.
+	Accessible
+	Often attached with brakes, simplifying deceleration
+	(Affordable – through NAV)
	Disadvantages
÷	Typically heavy weight
÷	Propulsion demanding
±	Less expensive

Table 1.2: Aspects of commercial CCSS.

1.3.2 Snowmobile

A motorized solution used for propulsion on snow is the snowmobile. The snowmobile works by having a continuous track that moves with the help of a motor and uses two skis in the front for steering. The tread pattern and size of the track decides how well the snowmobile handles different snow conditions. With a powerful engine and large contact surface, it is capable of driving in deep powder snow, as well as asphalt road crossings. Disadvantages include much noise, fuel consumption and not being allowed in the ski trails by law in Norway.

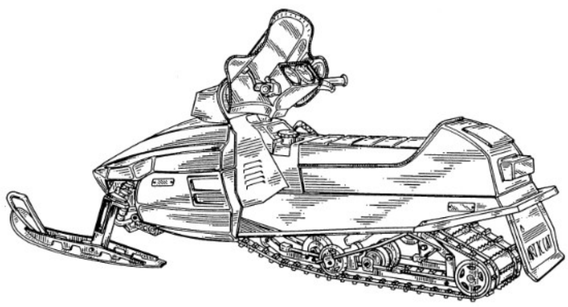

Figure 1.5: Snowmobile. [3]

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1.3.3 Electric Bikes

Electric bikes, hereunder also electric scooters, have become more and more popular in the later years as an easy means of transport in the city, the forest or mountain. The e-bike has a small electrical DC motor, either in the center of the front or rear wheel as a hub motor or a crank motor. El-motors can also be used for fatbikes, being an appropriate solution to cycling in the ski trail.

Figure 1.6: Bicycle with fatbike tires.

Chapter 2

Mechatronics

Combining the field of mechanical engineering with electronics creates the field of mechatronics – which is the integration of actuators, sensors, signal conditioning and power electronics to achieve mechanical movement. The movement is controlled by control algorithms, computer hardware and software. A mechatronic system translates physical forces into electrical signals and vice versa.

What follows is a short introduction covering the functionality of the control unit, the sensors and actuators. It is only a rough description as most of the equipment either is used in simple tests, was a part of the existing parts of the control system, or planned implemented at a later stage for controlling the motor. An exception is the brushless DC motor that served an important part in the thesis. [4]

2.1 Control Unit

Controlling of the different input and output signals in a mechatronic system is done by a control unit. The control unit is usually a microcontroller such as an Arduino and is essentially a small computer on an integrated circuit. It is used for controlling an electronic embedded system that processes and interacts with digital, analog, and electromechanical components. The circuit usually contains a CPU, memory, peripherals, and support circuitry. [5]

The CPU generates control signals, manages data flow and performs arithmetic operations according to the instructions in the created code. The memory is divided into non-volatile and volatile memory. The nonvolatile memory, the ROM, stores the microcontroller's program that tells the CPU what to do. The volatile memory, the RAM, is used for temporary data storage that is lost when the microcontroller loses power.

Peripherals is a collective term used to describe hardware modules the microcontroller uses to interact with the external system. It involves data converters, both analog-to-digital and digital-to-analog, clock generation, timing, analog signal processing with amplifiers, comparators and serial communication in different forms. The last of the peripherals are in- and output circuitry making the microcontroller able to receive and transmit signals to external actuators and sensors.

2.2 Sensors

Sensors are used to measure a variety of physical variables such as displacement, direction or tilt, stress and pressure. The sensor converts the physical variables into an electric signal the microcontroller can use. The different variables use different sensors to measure. In this project the sensors in focus are switches, potentiometers and force-sensitive resistors, often referred to as FSRs. [4]

2.2.1 Potentiometers

A potentiometer is a variable resistor and acts as an adjustable voltage divider. The resistance is manually varied by changing the position of a sliding contact across a uniform resistance.The voltage works as the input and is applied across the whole length of the resistor. The output is the voltage drop made by changing the position of the sliding contact in relation to the fixed contact. Because of the uniform electrical resistance per unit length in the fixed contact, the voltage drop per unit length is equal across the entire length. There are two main categories of potentiometers, linear and rotary, and both were proposed used in the thesis. Potentiometers usually have high accuracy and therefore preferred for a variety of uses. [6]

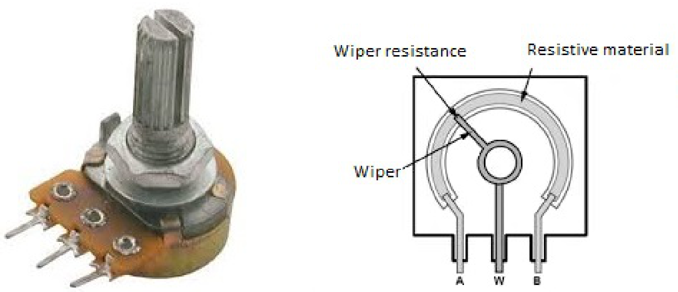


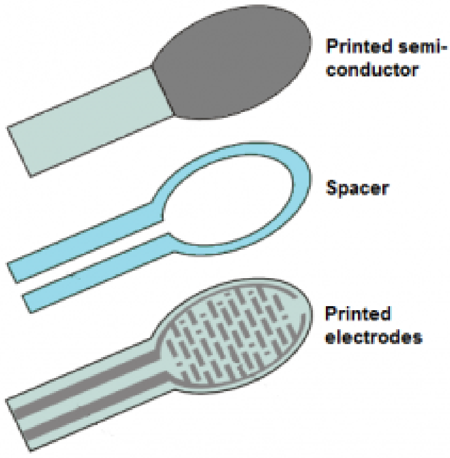
Figure 2.1: A potentiometer showing the internal structure with the resistor and the sliding contact. [7]

2.2.2 Force-Sensitive Resistors

Force-sensitive resistors (FSR) are a type of variable resistors that decrease the resistance with an increase of force applied to its surface. Generally, the change in resistance is proportional to the applied force. It is normally constructed as a polymer thick film consisting of two layers of both non-conducting and conducting particles separated by a spacer. Applied force to the film causes the particles to touch other conducting electrodes and decrease resistance.

FSRs are used to detect changes in applied force, but often have low accuracy. They are therefore not suited when high accuracy or specific weight measurements are needed, but more suited where ranges of response are sufficient. The device characteristics depend on the size, shape and materials used. FSRs exhibit different force-resistance characteristics, depending on the structure of the active area. The FSRs also have different sensing ranges, but a normal range is from about 20 g to 5 kg. [8][9]

(a) A square FSR.



(b) The layers an FSR is constructed of. [10]

Figure 2.2: Force-sensitive resistor.

2.2.3 Switches

Switches in mechatronic senses are used to turn on and off electrical equipment and are an important part of control system engineering. There are mainly two types of switches; mechanical switches and electrical switches. In the thesis, a focus will be on mechanical switches in terms of a push-button switch. [11]

A switch works by completing and breaking the circuit leading the current to either flow or not. When the circuit is open, the switch is off. When the switch is off there is no flow of current through the conductor and the equipment is de-energized. Turning the switch on means closing or completing the circuit. Completing the circuit is done by closing the path so current can flow and energize the system. In mechanical switches, two metal plates touch each other to complete the circuit and separate to open circuit. When pressing a push-button switch, the contacts or plates close, completing the circuit. When the pressure is removed, the contacts of the switch open and break the circuit. It is a momentary contact switch that opens the circuit with the use of a spring when pressure is removed.

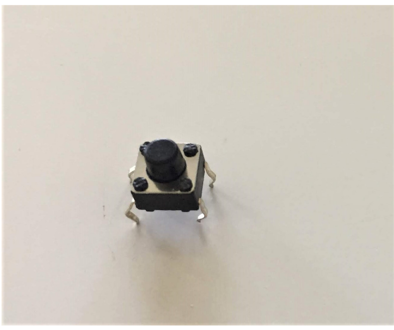


Figure 2.3: Push-button.

2.3 Actuators

An actuator, as opposed to a sensor, transforms electrical signals into physical variables. It is a transducer that takes in an electric signal from the microcontroller, converts it and controls a physical element. The name actuator implies physical motion, but it also includes other physical properties such as light and sound. In the project, the focus is on the DC motor, in particular the brushless DC motor. [12]

2.3.1 Brushless DC Motor

A brushless DC motor is an electric DC motor. The biggest difference between a brushless and other DC motors is the lack of brushes. These motors are very efficient and produce a large amount of torque at a wide range of speeds. The brushless motor was not invented before 1962 and has displaced brushed motors in many applications. Brushed motors have been in use since 1856 and are still used for electric propulsion in some areas. The brushes are however exposed to wear and needs replacement after some time. [13][14]

The internal workings of brushless and brushed motors are based on the same principles. To better understand how the brushless motor works, the function of the brushed motor will be explained in short.

Both motors have two main parts, a rotating rotor and a stationary stator. Brushed motors have fixed permanent magnets placed on the outside of a spinning armature containing energized windings or coils.The windings are connected to a commutator ring and are energized by brushes that connect the commutator ring to a DC power source. When the coils are energized, they create an electrical field that repels and attracts the permanent magnets in the stator. The motor can do work by converting this magnetic force into shaft rotation. The electric current flows to different sets of windings as the shaft rotates and continually changes the repulsion and attraction to keep the rotation.

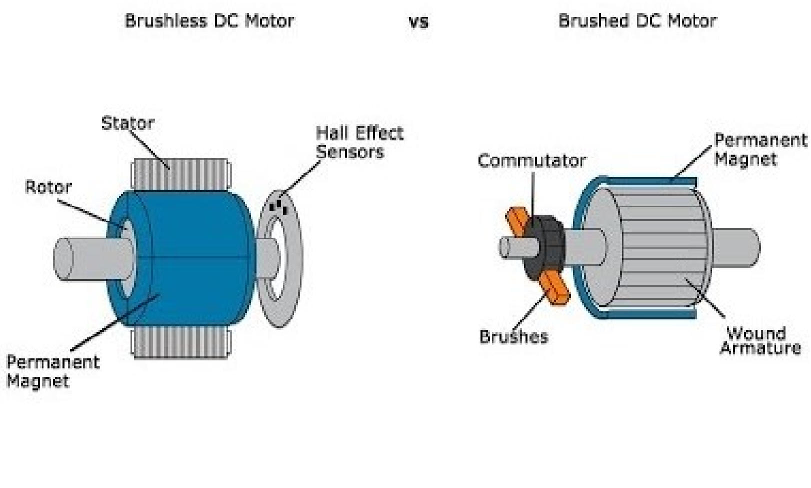


Figure 2.4: Simplified models showing the difference between a BLDC motor and a brushed motor. [15]

In BLDC motors the rotor and stator are switched. The windings now instead work as the stator. Therefore, a BLDC motor does not require a physical commutator since the windings are stationary. Since the permanent magnets now work as the rotor that rotates around a fixed armature, it overcomes the problem of connecting current to the armature. The need for brushes to connect the windings to the power source is eliminated. The windings are energized in turn, changing the electromagnetic field and continuing the rotation. The basic working principle of internal shaft position feedback is used in brushless motors to know which windings to energize. The pulses of current to the motor windings, provided by a controller, control the speed and torque of the motor. When the motors first were developed they represented a huge leap forward in technology with higher efficiency and lower susceptibility to mechanical wear. The differences between the motors is shown in figure 2.4.

The motors are known for smooth operation and being able to hold a constant torque, also when stationary and at low speed. The torque is the rotational force the motor delivers and is measured in Nm. It is proportional to the motor current: $T = k_t i_A$ – where T is the torque, k_t is a function of internal parameters and i_A is the current. The mechanical torque of electrical motors is used in an equation where the mechanical output power is found by multiplying torque and rotational speed. [16][17]

$$P_{out} = T_m \omega_n \tag{2.1}$$

The input power is found by multiplying the supplied voltage by the battery and the maximum current the motor can handle: $P_{in} = V i_A$. The efficiency of the motor is calculated as mechanical output power divided by electrical input power: $E = P_{out}/P_{in}$. By substituting the expression for input power and the expression for efficiency, the output power can be calculated:

$$P_{out} = V \ i_A \ E \tag{2.2}$$

Combining the two equations gives an expression for torque based on voltage, current, efficiency and rotational speed.

$$T_m = \frac{V \ i_A \ E}{\omega_n}$$

Chapter 3

Method – The Development Process

In this chapter, an overview of the development work done in the master thesis is described and presented using design theory and methodology. The theories and methods are used as guidelines in the development process and are applied to reduce the risk of failure and uncertainty in the project. The description of the methods used is presented universally so the method can be applied in similar development processes containing much uncertainty with a wide solution space.

The background also explains that the desired user group contains a great variety of users and is considered quite broad with different needs and challenges. Users of para-sports equipment are often in need of customization and adjustment possibilities to cover individual needs. The challenge of the wide user group was tried solved by starting the development off in a general manner. Solutions that solved specific user needs were not in focus in the early phase of the process and should be implemented at a later stage after the main concept has been chosen. While the user group itself imposes some limitations due to individual needs, the development process is still characterized by uncertainty because of the open solution space.

The process used is a mix of several suitable development methodologies and theories. Useful principles were picked to obtain a favorable result based on the time and resources available for the development project. To present the method, the phases of the development process covered by the thesis are defined in the next section.

3.1 Model of the Development Process

To define the area of the development process the thesis covers, a linear design methodology is first used as an example to give context. The development process using a linear approach can be divided into different parts making it suitable to present progress. A good approximation of a linear model is the stage-gate inspired model seen in figure 3.1 from Ulrich and Eppinger. [18][19]

The thesis covers the early stages of the development process. Compared to the model of Ulrich and Eppinger, the project was conducted in the phase of Concept Development, with signs of System-Level Design and a small portion of Detailed Design. As the mission

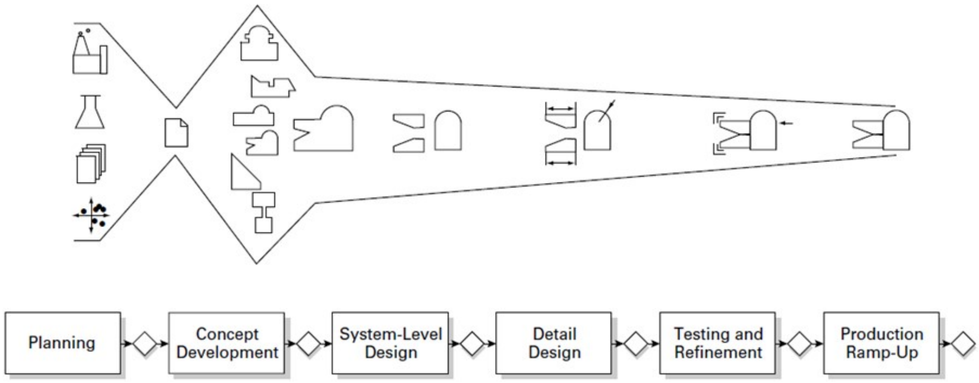


Figure 3.1: A linear development model inspired by Ulrich and Eppinger. [19]

statement describes, the thesis should find one main concept for further development. The order of the phases in the linear approach presented in figure 3.1, however, was not considered optimal due to the uncertainties and fuzziness of the project. In the thesis, the system-level design and detailed design was considered as a part of the concept development instead of individual phases. A more suitable model was therefore made to show the process.

3.1.1 Customized Model of the Thesis Work

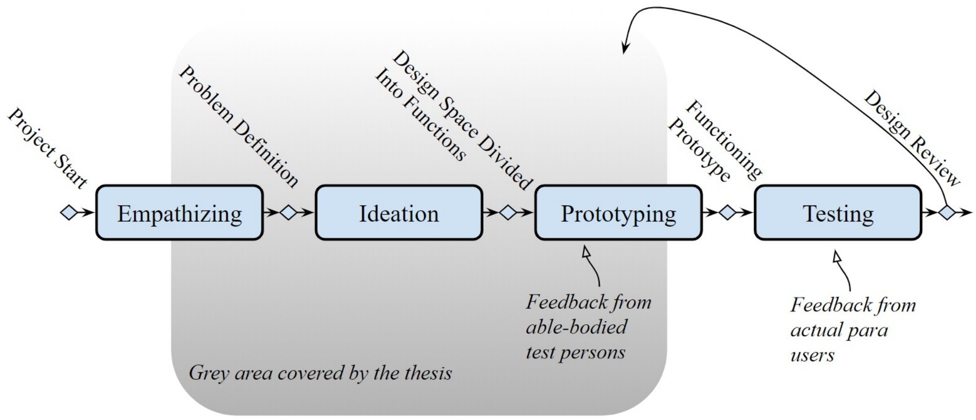


Figure 3.2: The concept development process of the project.

The model in figure 3.2 is customized with a more detailed display of the development process.Taking principles from different development methodologies to best fit the project makes the model a combination of several methodologies. The displayed boxes, empathizing, ideation, prototyping, and testing, were the different phases the development was intended to go through. It is worth mentioning that the phases, visualized as the four round-cornered boxes, in reality, were fuzzier, and the linear model is used to simplify the visual effects. The phases were more fluent and were worked with concurrently. The grey area, covering the ideation and partly empathizing and prototyping, shows the actual part of the process that was covered by the thesis work. As the grey square indicates, the realization of a final functioning prototype was not completed as was the mission of the thesis. The diamond-shaped boxes between the phases imply milestones during the process and are named in figure 3.2. Applying milestones was inspired by the linear model in 3.1 and the milestones were meant to track the progress for internal use. The customized model will be used to describe the different phases of the project throughout this chapter.

The last milestone seen in figure 3.2, Design Review, will be a critical decision point. With input from actual para users and managing personnel, it should be decided whether the concept is worth the resources to further continue the development. If the process is not killed, improvements should be made or prepared for "production ramp-up". If new iteration loops are to happen, as the arrow from the milestone in the figure indicates, the status of the process will "step back" compared to the linear model.

3.1.2 Empathizing and Defining the Problem Definition

The empathizing and knowledge generation, the first phase in figure 3.2, was inspired by Design Thinking. The phase was mainly conducted in the pre-master and was used to find the problem and user needs. Even though most of the empathizing was conducted in the pre-master, some empathizing was also conducted at the earliest part of the thesis work with the observation of the Para WC event in Lillehammer. New information gathered through the thesis work was not excluded, but instead implemented. The empathizing conducted in the pre-master is presented in Appendix B and the empathizing done in the thesis was presented in the introduction. [20][21]

The empathizing exposed the most important user need as assisted propulsion because of the strenuous and exhausting nature of the activity. The use of a CCSS requires a lot of upper body strength and was through firsthand experience considered heavy exercise, especially for beginners. Users are therefore often referred to CCSS-specific ski trails to go skiing.

Defining the problem began immediately at the onset of the thesis work. From empathizing and gathering of user needs, the knowledge gained was transformed into a mission statement and solvable challenges. The problem definition presented in section 1.2 is quite wide, and the development process has many unknown factors.

With the help of the user needs, the problem definition was broken down into smaller design challenges presented in chapter 4 Design Challenges. The design challenges make up the design domain in which the developing work of the thesis was conducted. Most of the technical design challenges presented in chapter 4 were explored during the prototyping from a mechanical engineering point of view.

3.1.3 Feedback and Development of Equipment for Para Users

Figure 3.2 indicates that it has been differed on whom the feedback is received. Individual customization will be needed for users with physical limitations, requiring better detail design considering safety and comfort. Para users tend to be less available and having bigger individual differences, being expensive in an early phase development process. The development of a novel product with a focus on the technology rather than individual preferences can, therefore, benefit from postponing testing with para users until one main concept is concluded.

3.2 Set-Based Concurrent Engineering

The problem definition and development process is characterized by a high degree of uncertainty and contains a wide solution space. The varying factors and the broad user group demand a flexible process that allows quick changes in the design. A methodology containing the flexibility the problem requires is set-based concurrent engineering. It is a part of new development methodology, derived from set-based design, and contains some of the same principles. [22]

The phrase set-based can be interpreted in different ways. In the thesis, the term set-based is understood as exploring sets of solutions in the form of different concepts that solves the same problem. The understanding of the phrase also involves physical range in terms of size i.e. the requirement and solution will be within a range.

3.2.1 Ideation and Separation of Functions

A principle of dividing a project into separate functions is often used in SBCE and was applied to the process quite early. The milestone of dividing the design space into separate functions was based on this principle. The principle is usually utilized at a fairly high level by dividing the project into functions such as development, marketing, management, and more. Marketing and management were however not considered important parts of this project and were discarded. Instead, the division into functions was applied at a lower level only covering the development. By focusing on the development, the principle was used to divide the design space into different functions, or parts of the product, as seen in figure 3.3. The purpose of applying the SBCE principle of separating the overall design into segments was to enable concurrent engineering by developing the functions at the same time. [23][24]

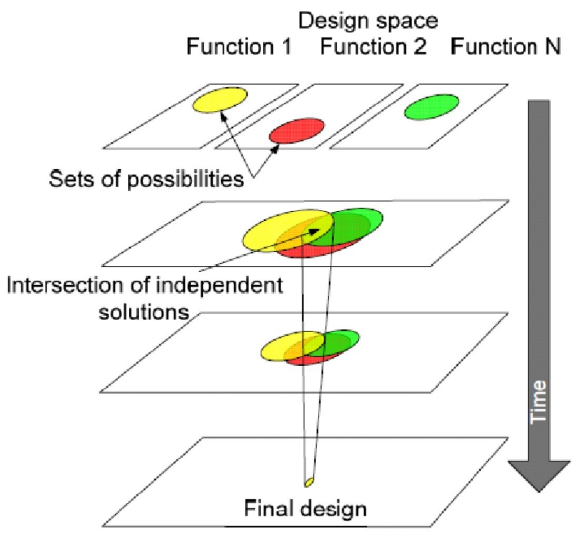


Figure 3.3: Model of set-based concurrent engineering. [25]

The ideation phase is positioned before the milestone of separating functions, but in reality, the two were closely connected and the process was flowing. The principle of dividing the design space was also a part of the ideation phase as the phase consisted of generating the concepts for the different parts of the design. How to best divide the design space was influenced by the ideas presented in the ideation phase and generated concepts changed with different suggestions of separation.

Combining the ideation phase and the milestone led to an initial ideation phase were rough ideas of the complete product were suggested. The initial ideation phase provided the foundation used to divide the design space. The division of the product into functions was done based on the rough ideas and resulted in the separation showed in figure 3.5.

In SBCE, the principle of separation should be applied so the functions are fairly independent. The separated functions in the thesis, drive system, frame design and detail design, are however dependent to some degree and impose limitations on each other. Being dependent, the functions could still be developed separately but had overlapping features imposing limitations that needed to be accounted for in the development. [25]

A new ideation phase was conducted after the division of the product into functions. The rough ideas were explored further in this ideation phase. By separating the development process it was possible to divide the amount of work and focus on different parts. The focus placed on each of the functions depended on the importance and influence at an early stage of development. The drive system, considered the primary function and most time-critical, went through the most thorough ideation.

In set-based methodology some critical elements of the design can be locked, when limitations are imposed by key principles of the design. The use of commercial skis was considered such a key principle. As the mission was to make skiing more accessible, customized skis would have a negative impact on the goal. The dimensions and distance between the skis enabling the sit-ski to fit the standardized ski track were also considered key principles and are described in section 4.6.

The ideation process revealed a wish to use and borrow from existing solutions and designs to use as a base for further development, combining them into a functional product. This also included investigating commercial products that could be used.

The process resulted in sets of solutions for each of the functions. The principles were applied to keep the process flexible and open to changes and adjustments when information about the solutions was revealed. By being open to changes, design decisions were delayed, differing from a linear approach where the concept is specified at an early stage.

3.2.2 Prototyping Phase

From the milestone, there was a fluid transition to the prototyping phase. The ideation phase led to sets of solutions for each of the functions that had to be explored. The sets of solutions were explored in the prototyping phase, narrowing down the design space.

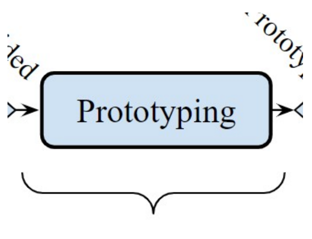


Figure 3.4: The part of figure 3.2 described in figure 3.5.

As shown in figure 3.5, the sets of solutions found in the ideation phase were separated into the functions and explored concurrently by prototyping.

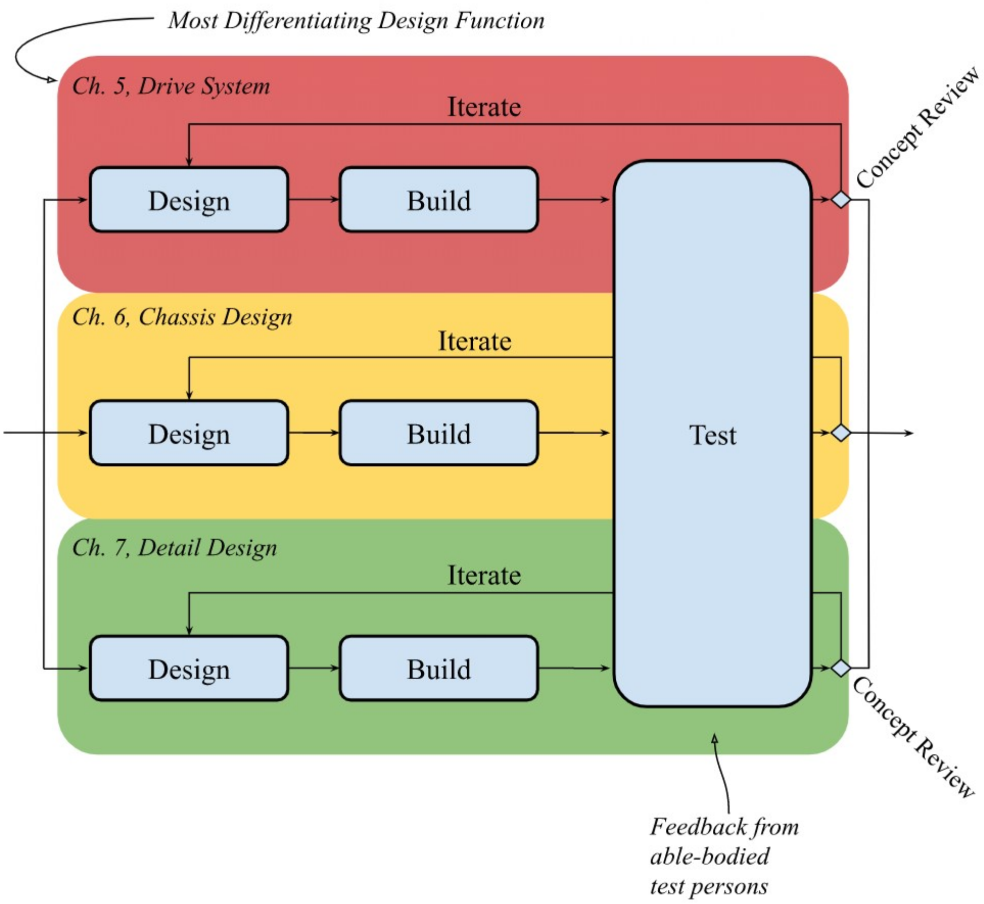


Figure 3.5: The prototyping phase.

The three concurrent design functions seen in figure 3.5 are described further in their respective chapters 5, 6 and 7 of the thesis. The design function displayed at the top of figure 3.5 and described in chapter 5, the drive system, has been the most differentiating function and therefore investigated the most.

During testing, concepts from each function were combined as testing separately or excluding one design function would be difficult. This is shown in figure 3.5 were the square representing testing covers all the functions.

Each function contained a set of solutions. The different concepts making up the sets were made into physical models, prototypes, to discover unknown factors. The solutions inside each function were explored in parallel to continue having a wide view of possible solutions. Through investigation, the concepts were weighted against each other using these prototypes and testing. The output from physical- and computer models, testing and also calculations were considered learning points, and was used to narrow the design space and converge towards an optimized solution for each function. A simplified model of the process conducted for each function can be seen in figure 3.6.

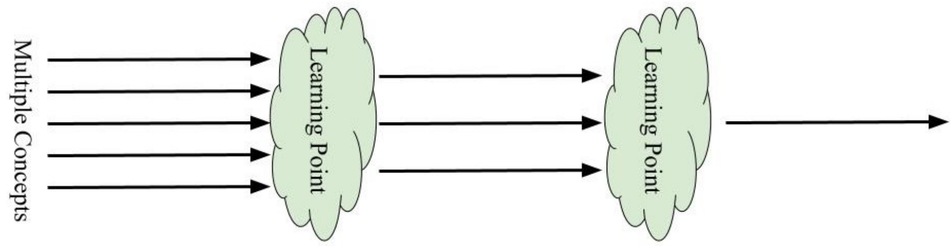


Figure 3.6: Model of set-based design.

Iterative Development

The learning points serve as milestones in terms of a concept review. These were presented after every design function test and made the phase iterative. The concept reviews were decision points of what should be prioritized for improvements and assessment of function. Results of each iteration provide knowledge from testing and building, gradually narrowing down to the most ideal design of a functional prototype. Through the iterative process, the prototypes evolved from the initial quick prototypes towards functional prototypes.

The iterative work was a continuous process and each iteration involves planning, designing, building, testing, and reviewing. Larger and smaller changes were introduced to the prototypes, solving problems with the design experienced and observed during tests. Changes were applied when tests revealed answers to uncertainties with the design. Minor changes often took shorter time to implement while greater changes required more work and resources to implement or build. The amount of learning can depend on the extension of the changes, but smaller changes also lead to greater learning in some cases. Using the information and knowledge found, the process can stay flexible and be ready for unforeseen changes. The iterations and reviews were used to avoid late learning and design re-loops. The concept reviews helped keeping track of progress as and managing an iterative process can be difficult. [26][27]

While the drive system experienced several iterations of tests, the detail design was not developed much in the first iterations. For instance, ergonomic parts were not prioritized initially. This resulted in feedback from test persons of a little pain by the knees, but it was supposed to not affect the evaluation of the other design functions.

The prototyping process was interrupted and therefore did not result in a final functioning prototype constructed for testing with actual para users. It is reasonable to say that many of the prototypes produced were functioning, but testing was only conducted with able-bodied users due to safety reasons. Para users often require more individual customization for testing that was not prioritized early in the development process. The making of the prototypes and theories used in the prototyping process is elaborated further in the next section.

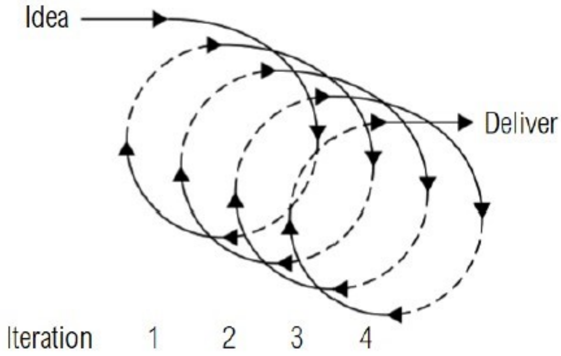


Figure 3.7: Model of development with iterations. [28]

3.3 Prototypes and the Prototyping Process

In the process of narrowing the design space and investigate the concepts, converging to the preferred solution, a theoretical and abstract approach is not always sufficient. To get a deeper understanding, finding unknown challenges and inspire creativity, physical models are often applied in development processes. Physical models are often referred to as prototypes. There are different definitions of prototypes, but they can be explained to be physical or abstract approximations of a product or part possessing one or several of the final product traits. [29][19]

In the project, the investigation of the different concepts is aided by prototypes and prototyping. Several kinds of prototypes have been used to increase knowledge about unknown elements of the concepts. The different types of prototypes used are described using prototyping theory and classifications.

3.3.1 Classification

As the thesis work was in an early phase of the development process, simple and rough prototypes were used to explore the concepts. Ulrich and Eppinger [19] describe the use of prototypes. They divide prototypes into two main categories; early prototypes and milestone prototypes. The simple prototypes built in this project fall in the first category being that they show how the product should work, look or feel. The milestone prototypes are prototypes closer to the production with models showing most of the features of the product.

The functionality was considered more important than the look and feel of the prototypes, as the function of the concepts were explored at this point of the process. The earliest prototypes were especially important to investigate how the product should work. They served as proof-of-concept prototypes as described by Ullman [30]. The critical function of propulsion being saturated by uncertainties, the models were used to investigate the plausibility of the project. To make the first prototype, off-the-self-parts were put together with easily accessible material such as wood, resulting in rough models. Rapid prototyping using 3D-printing and laser cutting of MDF-plates were used to realize more critical custom-made parts.

To distinguish the different prototypes built as a part of the thesis, two terms are used. The proof-of-concept prototypes meaning prototypes that exhibit some vital, but not all functions of the expected design, have been borrowed from Ullman. The early models of the drive system were considered proof-of-concept and were used to investigate the ability of the motor to provide propulsion of the sit-ski. The second term used describes a prototype closer to the expected end design. The goal of the thesis was to narrow the design space, choosing one main concept and working towards what is called a functional prototype. The functional prototype exhibits practically all the functions of the expected design.

3.3.2 Fidelity of the Prototype

The amount of detail and how close the models are to a final product is understood as the resolution or the fidelity of the prototype and is used to describe the roughness. The rough prototypes made in the beginning were characterized by low fidelity. The fidelity of the prototype can affect the function and performance with testing of the prototype. While the models were rough and influenced by the fidelity, they were still able to reveal unknowns and drive the development forward. It should be mentioned that the fidelity of a prototype will affect the test results and must hence be considered in the evaluation of concepts. [31]

The different functions and solutions had different degrees of complexity. The amount of investigation and work needed depended on the complexity of the concept. To achieve the same level of fidelity, the complex parts such as the rubber track demanded more work and resources.

For the drive system, the fidelity and complexity influenced the motion resistance of the prototypes, meaning the results of tests were considered somewhat skewed. It is reasonable to assume that the experienced difference in internal resistance due to the fidelity was greater for the track than the wheel prototypes. Being influenced by the fidelity, the results were not seen as quantitative but instead qualitative. The complexity of the chassis concepts resulted in postponing the building of several of the concepts, only using the least complex, since testing of the drive system was considered the most critical.

3.3.3 Set-Based Prototypes

One of the chassis prototype's most important functions was to facilitate testing of the drive system. To facilitate assessing multiple prototypes of the drive system, the principle of set-based prototypes was applied to the chassis prototype. Set-based prototypes are made adjustable and it is, therefore, possible to make changes and test several sub-functions with little effort. The prototypes of the drive system all have different fastening mechanisms in terms of the suspension and by configuring the chassis model to the different drive concepts, multiple solutions could be tested with few changes. With the easy change of the drive system, the sit-ski could assess different wheel sizes and the continuous track during one test, keeping the same skis, sitting position and conditions unchanged. [32]

3.3.4 What Prototypes Prototype

A different way to classify prototypes is to look at the purpose of the prototype. Houde and Hill describe this in the article, *What do prototypes prototype* [33], where prototypes are divided based on their intended use. A clear purpose of the prototype to communicate the solutions ease the process of narrowing the design space with less use of resources. Prototypes can, according to Houde and Hill, be described using three dimensions as seen in figure 3.8. When the prototype shows the complete user experience it is called an integration prototype an is usually placed in the center of the figure.

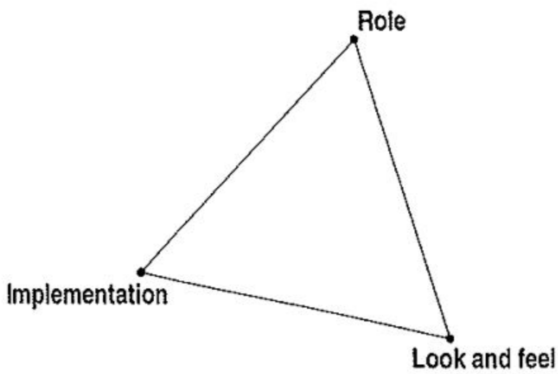


Figure 3.8: What prototypes prototype. [33]

The prototypes built in the work of the thesis served different purposes, but most of the prototypes were placed along the same dimension. The early rough prototypes meant to explore concepts for propulsion, the power of the motor, grip and traction, were a part of the implementation dimension where prototypes aim to answer technical questions. Through building and testing the different concepts, the goal was to find how the product should work and to discover specifications for further development.

Though most of the prototypes were made in the dimension of implementation an underlying purpose of the prototype was to describe the functionalities users benefit from and what it does for the user. This is described as the role dimension and became more important after the initial prototypes were made.The whole purpose of the final product was to make skiing easier for people with limitations and the development of a device not providing this help would be considered a failure. It was therefore important that the prototypes showed how the user benefits. To embrace the role dimension fully, actual users were expected to participate in the testing. Such a test was not possible and since the prototypes only were tested by able-bodied users, the experienced benefit will not be as relevant and quality assured.

Most of the prototypes in the project were made to a lesser degree in the look and feel dimension. This is shown as the fidelity of the prototypes were too low to give a good result in these areas. Even though the prototypes were not made to give results here, some of the prototypes touched into this dimension as the experience of interaction during testing contributed to and revealed unknown problems. The low fidelity could explain some of the problems that were revealed, but the experienced need for a damper was not considered important when defining concepts. At later stages of the development, this dimension should be more in focus when fidelity of the prototype is improved. The look part of the dimension was not in focus for the duration of the work with the thesis.

3.4 Testing

The building of prototypes uncovered some challenges and revealed uncertainties, but by performing tests on the prototypes other answers and problems were exposed. Testing was used together with prototypes to achieve a deeper understanding and was an important part of the development processes. As the prototypes were built, testing was conducted to assess their functionality.

Before each test was conducted, the objective of the test was set to increase the relevance of the output. By having a clear focus area, the tests contribute in a greater sense to the development. The different functions of the CCSS were combined as it was difficult to separate testing into unrelated functions/fields. Combining the functions to test resulted in output for several of the functions at the same time. Objectives were often made for each function of the combined prototype to get the most out of testing. Even though the tests usually had a clear focus, other observations were likewise noted and used, especially unknown elements that were exposed.

Throughout the process, tests were performed to investigate the different solutions. The first test was to investigate propulsion in general, as the propulsion was critical for further work on the project. The proof of concept prototype using an electric bicycle motor was tested to investigate the plausibility of the project. The purpose/objective of the tests varied through the course of the project, and several objectives could be tested in the same test. A test logbook, containing the objectives, test object, conditions and results, is given in Appendix A.

Through the iterative product development, building, testing and retesting of the different possible solutions and concepts could be executed simultaneously. Test results produced were used in the development of the next iteration.

The tests were conducted by able-bodied users, for safety and availability reasons in the earliest stages of the process. Later prototypes were to be tested by actual users as the fidelity and safety of the prototype increased. By testing with able-bodied users the results are somewhat subjective and based on experience.

Test conditions varied due to changes in weather, altitude and snow conditions. A goal was to cover a wide range of conditions and because of the rapidly changing weather, a variety of conditions were available for testing.

3.5 Calculations

The project had a practical approach to development with concept development, prototyping, testing and iterations. Only simple calculations to aid assumptions were used in the development. The rough calculations of simplified structural systems and the motor were used to show numerical results interpreted qualitatively. It was meant to be additional to the physical development in focus only used by the developers as the results being qualitative and needed to be put in context.

Due to the outbreak of COVID-19, some changes had to be made in terms of the thesis. The main changes meant it was not possible to follow the practical approach intended. The use of prototypes and tests to confirm assumptions or expose them as false became difficult to proceed with. Instead, calculations had to contribute to a larger part of the project. With a more theoretical approach, calculations and drawings were used to find comparable results from different concepts that could be used in the development.

The set-based approach was still the foundation of the project, where investigating the different parts and making comparable results were done to make the best choice of solutions.

Chapter 4

Design Challenges

The most noticeable problem observed through the empathizing led to a quite broad problem statement of assisting propulsion. To facilitate development, the broad problem definition was broken down into smaller more tangible problems of engineering character. Breaking down the problem in smaller parts converged the problem space into a set of specific design challenges.

The set of design challenges make up the design domain for the product and worked as the foundation for the development work. Most of the challenges are connected and relying on each other. This chapter can be seen as a result of the investigation of user needs – as well as knowledge gathered from prototyping – and will present the most important design challenges. The exploration of the technical design challenges presented in this chapter will be described in the following chapters.

4.1 Drawbar Pull

The drawbar pull of the vehicle is the pulling force acting on the user from the motorized sit-ski. As assisting with propulsion was described as the most important improvement point to solve, the drawbar pull of the vehicle will play a key role in the design. It was early decided that the sit-ski should be equipped with a motor as the aid of ensuring propulsion, as mentioned in section 7.1.

The device should be able to work in an assisting manner even in the steepest slopes found in ski trails. Hence, substantial motor power is needed. However, there are other design challenges to overcome and the motor is only to count as support to the user double poling, so the ideal size of the motor is limited. The amount of motor power needed would be greater if the vehicle was intended to be self-propelled. Besides that, laws of motorized vehicles must be followed and the weight of the equipment should be minimized, which affects the choice of a motor as well as other design challenges described in this chapter.

The desired drawbar pull will vary from user to user. For instance, a beginner of heavyweight and bad physical shape might need continuous assistance with propulsion, and wish for more power than a 250 W motor can supply. On the other hand, a competing athlete might only need a little push in the steepest uphill and find it embarrassing to get help with propulsion. Additionally, it is reasonable to assume that an experienced athlete will prefer a neat solution with less motion resistance and very low weight. As a result, one cannot expect to find one single solution that meets all the varying preferences. Instead, a compromise might be achievable – which is also the case for the design of the drive system. With theoretical background, however, the development is more likely to result in a beneficial solution. Therefore, the next sections will outline the physical parameters affecting the drawbar pull.

Theory on the Parameters Affecting Drawbar Pull

The drawbar pull, F_d, can be described as the net thrust or pulling force available from the vehicle as a system. It is dependant on the motor power, total motion resistance and traction, which is described in section 4.2. Drawbar pull will work as the force pulling the user sitting on the sit-ski and can be defined as:

$$F_d = F_t - R_c \tag{4.1}$$

where F_t is the tractive force and R_c the motion resistance working against the direction of movement, the x-direction. Both F_t and R_c are functions of slip.

The weight of the user is not included in the term F_d described in this chapter, and the user's contribution to the propulsion is not included in the considerations. Motion resistance R_c includes internal friction in the drive system as well as wind drag that will increase with the square of the velocity. The tractive force F_t will be equal to the rim pull acting on the shaft of the hub motor. This means that tractive force F_t equals the tractive effort F_e minus the horizontal rolling resistance mainly from the snow being compressed, which is excluded from R_c.

The drive force F available from the motor, also called the gross thrust, can be defined as:

$$F = \frac{T}{r} \tag{4.2}$$

where T is the motor torque and r is the deformed radius of the drive wheel — two important parameters to consider for the design. For the electrical hub motor used in the thesis work, the gear ratio was equal to one and is therefore not included in the equation. The effect of the product of angular acceleration and inertia of the wheel is neglected.

If the tractive effort F_e should be approximated with equation 4.2, no slippage is assumed as a result of a sufficiently high coefficient of traction μ_t, seen in equation 4.7. For solid contact surfaces like asphalt, this assumption is typically valid, as well as for studded tires on icy conditions. However, when snow is the contact surface, some degree of slip is typical, as softer snow yields. Once the drive force F is bigger than potential tractive force F_{max}, seen in equation 4.4, wheelspin will occur. This will be described further in section 4.2.

In general, considering the challenge of optimizing drawbar pull to assist with the propulsion of the sit-ski, the prototype should be designed to increase tractive force and reduce motion resistance.

4.2 Lack of Traction

The drawbar pull F_d of a vehicle relies on sufficient traction. For the motorized sit-ski, the tractive force will be limited by the shear strength of the snow surface of the ski trail. Once the shear stress applied on a material exceeds the shear strength, plastic deformation will occur and energy will be lost to the circumstances.

The shear strength of the surface material can be predicted with Mohr-Coulomb failure criterion:

$$\tau = c + \sigma \tan \phi \tag{4.3}$$

where the two material parameters c and ϕ are independent and defined as the apparent cohesion and friction angle, respectively. $\tan \phi$ is the coefficient of internal friction μ of the material. σ is the normal stress on the surface of shearing. The Mohr-Coulomb failure criterion with the material parameters of cohesion and friction angle can be used to describe snow. [34]

The tractive effort from the drive system of a vehicle is developed from the shear stress on the terrain surface. Equation 4.3 can be used to estimate the maximum tractive effort developed from a tire or track. [35][36] Assuming uniform contact pressure over a known contact area A of a tire or track with normal load W_d, the potential tractive effort available from the surface material can be predicted by:

$$F_{max} = \int_A \tau_{max}\, dA = cA + W_d \tan \phi \tag{4.4}$$

The equation shows that the maximum tractive effort depends on the material parameters $\tan \phi$ and c, and how they correlate with the design parameters A and W_d. When the snow behaves like a frictional terrain such as dry sand and $c \approx 0$, the maximal tractive effort is dependent on the normal load W_d. On the other extreme end of the contact surface conditions, if the snow behaves like a cohesive terrain like saturated clay, $\tan \phi \approx 0$, the maximum tractive effort depends on the contact area A.

The material parameters for snow, measured in two experiments, are displayed below to show an example of the magnitude for relevant snow conditions:
$c = 1.03\ kPa$ and $\phi = 19.7°$ (U.S.),
$c = 6\ kPa$ and $\phi = 20.7°$ (Sweden). [37]

Consequently, given average snow conditions with significant cohesion, increasing the contact area A and normal force W_d will result in increased tractive effort F_e. This will increase the assisted propulsion to some extent. The design parameter A, the contact area, is mainly dependent on the drive system, covered in chapter 5. while the design parameter W_d, the normal force on the drive wheel, is mainly influenced by the chassis design, covered in chapter 6.

An important variable considering traction is the longitudinal slip, which is defined as:

$$i = 1 - \frac{v}{r\omega} \tag{4.5}$$

where v is the longitudinal velocity of the vehicle, r is the radius of the wheel and ω is the angular velocity, as shown in figure 4.1.

To show a functional relationship between force, slip, terrain values and design parameters, the tractive effort can be described as a function of slip for tracks. Assuming uniform stress distribution along the contact length l of the track, so the normal pressure σ on the track is equal to W_d/bl, the tractive effort-slip relation is expressed as:

$$F_e = b \int_0^l \tau \, dx$$

$$F_e = (cA + W_d \tan\phi) \left[1 - \frac{K}{il} \left(1 - e^{-il/K}\right) \right] \tag{4.6}$$

where K is the shear deformation modulus, i is the slip, and A is the contact surface area. l is the length of the contact patch. The expression in the left bracket can be recognized from equation 4.4. In general, the expressions of tractive effort F_e does not include any subtracting term for a force of resistance. Hence, the tractive effort and will be bigger than the tractive force F_t, which again will be bigger than the drawbar pull F_d.

A design parameter of interest in equation 4.6 is the contact length l. Consider a change of drive system parameters. By reducing the track length l by half, as well as keeping the contact area A constant by doubling the width b, and keeping the tractive effort F_e and normal load W_d constant, the resulting slip i will be reduced by half. As a consequence, one can conclude in general that a longer track will slip less if it is to develop the same tractive effort. Note that minimizing slip is similar to maximizing traction. [37]

As the snow conditions are varying from hour to hour and location to location, the actual values of c, ϕ and K will be hard to determine for the ski trail. Hence, a theoretical model like equation 4.6 is not of great significance for the sit-ski design, but can work as a guideline in the evaluation of concepts and aid in understanding the influence of slip. Calculating tractive effort as a function of slip can additionally be done for tires with another equation [37], but regarding the thesis, with the high number of unknown factors, the relevancy is limited.

4.2.1 Coefficient of Traction

The coefficient of traction can be defined as:

$$\mu_t = \frac{F_d}{W_d} \tag{4.7}$$

where F_d is the drawbar pull and W_d is the normal force working between the tire or track and the contact surface. The coefficient of traction is a common parameter used for comparing the properties of vehicles considering traction. Since μ_t is dependent on the drawbar pull that includes motion resistance, it will rely on some factors not related to the properties of the contact surface. For instance, high velocity will increase the wind drag and thereby reduces the drawbar pull, so the value of the coefficient of traction will decrease. It is worth mentioning that the drawbar pull for a vehicle in the previous section was given as a function of slip. Therefore, comparing the coefficient of traction of different drive systems should be done with the same slip and same conditions in general. The coefficient of traction is more commonly used for vehicles with wheels and rigid contact surface.

To compare the traction for tires and tracks for relevant surface types, numerical values exist. According to Burch [38], the coefficient of traction for packed snow for tires and tracks can be 0.20 and 0.27, respectively. Hence, it is implied that a vehicle will have 35% more traction with tracks than tires. While for the surface of ice, the coefficient of traction

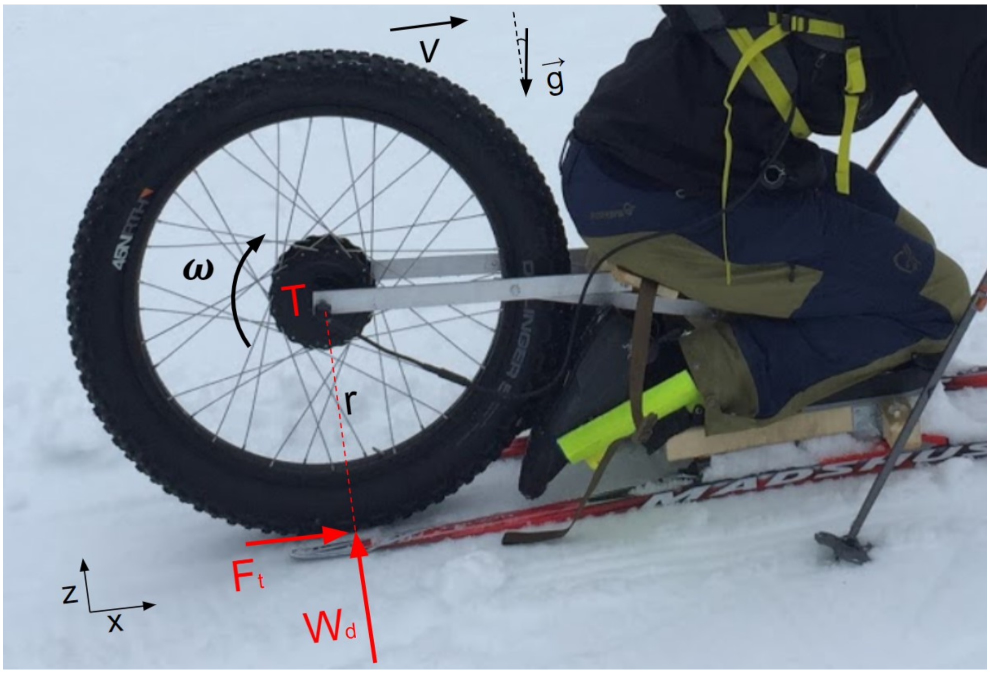


Figure 4.1: The forces acting on the drive wheel of a prototype from the snow.

is equal to 0.12 for both tires and tracks, according to the book. This will naturally rely on several design parameters for the specific drive system and the present weather and snow conditions, so the numerical values are only to be interpreted as general predictions.

The magnitude of the coefficient is interesting for the thesis work as the weight on the drive wheel of the prototype is a key parameter. Coefficient of traction can hence be used to estimate the potential tractive force the sit-ski can perform, and to evaluate concepts before decision-making. It is reasonable to assume that a drive system with a track instead of a tire will have an increased coefficient of traction, less slip and increased rolling resistance. [39]

The design of the tread pattern is also a crucial factor for the coefficient of traction. If a wheel is used, the choice of tire and correlating tread pattern should be optimized for traction on snow. It should be pointed out that for driving on snow, full slip should be avoided since the polishing effect will result in the snow being more like ice with lower coefficient of traction.

4.2.2 Normal Force on the Snow

Sufficient normal force W_d on the drive system is crucial for the vehicle's tractive force F_t. W_d is a parameter easily influenced by the chassis design. Force of friction increase with the normal force until the shear strength of the snow is reached or slip occur. Applied weight on the drive wheel is therefore vital for assisting with propulsion and a key factor for success for the motorized sit-ski. However, the ideal distribution of weight between the drive system and skis is unknown. Too much normal pressure will increase resistance from the snow. The deeper the drive wheel or track goes, the more motor power will be needed.

4.3 Destruction of the Ski Trail

In Norway, recreational skiing is a popular activity and keeping the ski trail in good condition is important. If the motorized CCSS would destroy the groomed ski track or worsen the conditions, other recreational skiers would disapprove it, which could lead to certain ski trails prohibiting the use of the device. To minimize the destruction of the ski trail, the drive system should be designed to reduce the stress applied to the snow, for instance by increasing the contact area.

The destruction of the track is highly dependant on the snow conditions. Under some conditions when the snow is soft, for example right after snowfall or when it is cold and freshly groomed, destruction will be problematic to avoid. Under these conditions, the shear strength of the surface might be lower than what is needed to resist the stress from the tractive force of the vehicle, so the drive wheel will slip.

In addition to reducing traction, slip should be avoided since it will cause wheelspin that will impact the print on the ski trail, leaving a deeper mark. Full slip is considered the worst case, and appears when the velocity v of the vehicle is zero while the drive wheel is rotating. This results in digging, leaving a hole in the ski trail. By increasing the contact area of the drive system, while the normal force remains the same, the shear stress of the snow will be reduced, resulting in less destruction of the ski trail.

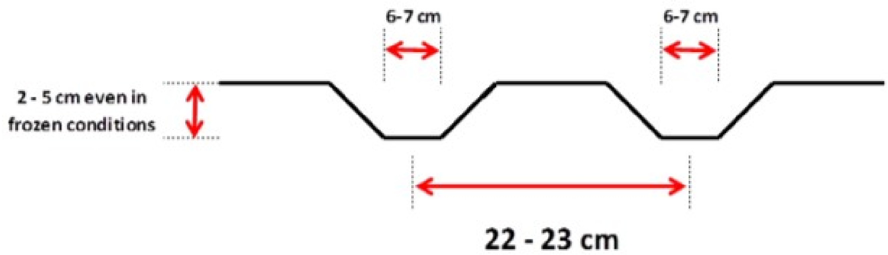


Figure 4.2: Ski track specifications. [40]

An important aspect is where the drive wheel of the motorized sit-ski should be positioned and act in the ski trail. Classic skiers use the groomed ski track with two parallel grooves, divided by an elevated center part. The middle of this track – the section between the parallel grooves where skis are placed – is often 5 cm high and 10 cm wide as implied in figure 4.2. This area is somewhat less compressed compared to the grooves and therefore able to withstand less force before fragmentation. The impact of the drive wheel in the middle of the ski track can be seen in Appendix A Test Logbook.

A solution to the challenge of destruction of the ski track can be prevented by avoiding the drive wheel from working at the fragile middle of the ski track in uphills. In uphills, when the pull from the motor is high, the user can maneuver out of the track and ski in the free section of the trail. However, in downhills, the user might need to be in the groomed track to maneuver through corners and obtain increased controllability of the sit-ski at higher speeds. This action will not destroy the tracks because the motor will not be needed and therefore not be applying significant shear stress on the snow.

4.4 Variation in Snow Conditions

The device should be able to operate in several snow and weather conditions. If not all, it should cover the most crucial or most usual range of conditions. Developing a vehicle that works in one optimum condition might not fulfill the mission statement. This means the drive system should have enough traction and minimum slip on a range of snow conditions that is beneficial for the users, noting that different types of snow conditions require different solutions.

A set of conditions could be selected and prioritized. The kind of conditions where the users have the greatest need for assistance is where it is most important that the motor has sufficient traction and drawbar pull. It is reasonable to assume that lose conditions with much new unbound snow is the type of condition it is toughest to ski in a CCSS. While double-poling in lose conditions, the poles tend to break through the upper snow level, resulting in the activity of DP being strenuous. Hence, it should be considered to prioritize this set of conditions for the sit-ski design, if a decision is needed.

(a) Freshly groomed tracks of cold fine snow. **(b)** Old wet snow with coarse grains.

Figure 4.3: Two widely different snow conditions.

Snow conditions – affected by temperature, moisture, snow grains and grooming – vary greatly over time during the winter and for different locations. Snow grains develop by aging and history of temperature variations. Ski trails along the coast, for instance, will have another set of snow conditions most of the winter, compared to ski trails in the mountains. An optimal solution might not be similar for different regions.

The conditions can also vary greatly within the same trail system. As an example, see Appendix A Test Logbook, the test day of 19.02.2020, when the contrast was huge between the snow conditions of the two locations in the same trail system of Bymarka.

4.5 Weight of Equipment

The motorized sit-ski should be designed with respect to weight reduction. In general, all racing sports have equipment designed in regards to weight minimization, to optimize speed and reduce energy consumption. Lower weight will increase maneuverability and make the activity less exhausting. The weight of the motorized sit-ski should not exceed a weight the user is not able to move by DP, in case of malfunction or loss of battery power far from home. If the weight of the sit-ski exceeds this limit, a comprehensive design should include a solution allowing a skiing partner to help the user by carrying part of the weight, such as the battery or a heavy part of the drive system. As the product is to be used as an assistive device, it should be possible to use it as a normal CCSS, maybe by removing the motorized drive system.

Figure 4.4: Athletes in action on light-weight CCSSs during WC in Lillehammer December 2019.

4.6 Positioning of the Drive System and Boundary Conditions

A design challenge is to develop convenient solutions to the placement of the parts that work as the propulsion system, with respect to the CCSS and the user. The position of the drive system, motor, control box and battery should not interfere with the movement of the skier in exercise. The assistive equipment should not occupy too much space, but have a compact design, be effective and be intuitive and easy to use.

The positioning of the drive system is limited by some factors. The drive system cannot act directly on the skis but should work somewhere else as the system is required to be in contact with the snow to transfer power. This limits the positioning of the system to either the side of the sit-ski or the center, between the skis. DP with the parallel motion of the user's arms on each side of the CCSS makes the space on the sides of the sit-ski unavailable since the system should not interrupt this motion. The only position left is therefore in the center. Regarding the position of the drive in the longitudinal direction, ensuring sufficient normal force on the drive wheel should be prioritized, so behind the skis might not be an optimum position for the drive.

The width of the ski track, 22 - 23 cm displayed in figure 4.2, also works as a boundary condition for positioning equipment. Above all, the width determines the gap between the skis and therefore the width of the system. As the preferred position of the motor is in the center, the width of the higher middle of the groomed track restricts the choice of the width of a belt or tire.

Additionally, the space occupied by the body of the user works as a boundary condition of where the drive system cannot be positioned. Given that the drive system not should be positioned too far back to ensure sufficient normal force, the system should be positioned as close to the skier as possible. There is limited space beneath the user that can be utilized to position the drive system. The height of the space under the user is lower than the diameter of a standard bicycle wheel of 26", therefore, such a drive system must act behind the user even though it is not ideal.

4.7 Motor Controlling

For a comprehensive solution – a satisfactory product for the experienced sit-skiers – motor controlling is an essential challenge to solve in an ideal manner. Extensive testing with users might be necessary to find a pleasing solution that is not disturbing to the DP. If the motorized sit-ski should be included in low effort-ski sessions, the interaction between user and motor control must be neat.

A control system for adjusting external propulsion aid to double-poling is not common and do therefore have many unknown factors. There are however some similar motor controlling methods where a motor works in an assistive manner, i.e. in modern electric bikes. On the CCSS there is no easy way to measure momentum or effort to control the assistive power delivered from the motor. Another solution for electrical bikes is manual control in the form of a thumb throttle. Such controllers cannot be copied directly but might be used as inspiration. A control panel to be operated by the user is possible to implement in the design, if made convenient. To measure the angular velocity of the drive wheel of the sit-ski prototype, slip must be taken into consideration.

4.8 Comfort and Suspension

Using the device should feel relatively comfortable for the user, preferably more comfortable than a usual CCSS. Discomfort in the form of sore muscles due to prolonged activity is a natural part of the sport of skiing, but pain from pressure points on the legs should be avoided. Knees, feet and the seat are vulnerable body parts. Hence, ergonomic parts should be designed for the interface between CCSS and the user.

The suspension of the prototype should be designed to work both in and outside the groomed track and facilitate sufficient normal force irrespective of height difference between the drive system and skis. When the CCSS is in the groomed tracks, the height difference between the drive wheel and the skis can be 5 cm, but when skiing outside of the track, the trail will be flat resulting in no height difference between the skis and the drive. The suspension should also be able to handle obstacles the sit-ski might face in the trail such as holes in the ski trail, bumpy formations in the ski track or blocks of ice.

4.9 Standard Parts

Considering commercialization of the end product, the development of the motorized sit-ski should facilitate a high ratio of standardized parts, and as few customized parts as possible. Using well-known products is also beneficial due to its availability and quality-assurance after decades in the market. As an example, using a commercial bicycle wheel of standard diameter 26" is more likely to work as expected in the first test, than a rapidly in-house developed wheel of theoretically optimized dimensions.

Reducing the number of parts will simplify assembly – keeping in mind the vision to reduce cost and production time. Assistive equipment for para-sports is often expensive, so reducing the price tag of the end product is a goal to make it affordable for more users. However, the early phase product development and prototyping will prioritize functionality, proof of concept and essential challenges to be solved, while standardization is subordinate.

4.10 Adjustability and Individual Preferences of Sitting Position

A comprehensive solution of the product should be adjustable to serve as an aid to as many different users as possible. A functional prototype should fit as many body sizes as practically feasible, while the concept development should not be restricted by this challenge. The variation of impairments for the intended user group is wide. Different types of sitting positions are used for different types of injuries, so one single sit-ski can not fit them all. This is described in Appendix B, in the pre-master in section 2.7 CCSS and Sitting Position.

One critical aspect is whether the sitting position is rigid or not. A moving sitting position has some benefits, but is not an option for competing athletes. A rigid sitting position with a seat height lower than 40 cm is the only legal solution, considering the rules for competitions. As professional athletes want their training to be as specific as possible, they will not use a CCSS with a sitting position different from what they use in competitions. However, competing athletes are not in the group of users in the greatest need of the concept of a motorized sit-ski. The design will hence not be optimized for the experienced athletes at this stage, but their knowledge about the activity of CCSS will be utilized in the development. [40]

This design challenge will not be prioritized in the concept phase of the development, but included in subsequent iterations. The thesis work will initially focus on other design challenges, using able-bodied test persons with preferences that might differ from para skiers.

4.11 Maneuverability

To steer, turn and maneuver the sit-ski should not be too demanding. A heavy sit-ski will be harder to maneuver out of groomed ski tracks. With two long parallel skis, the design parameter most critical to maneuverability might be the weight of the sit-ski as a system. The point of gravity should be as near the ground level as possible. Knee support, ergonomic parts and straps should ensure that movements of the user are transformed in a responsive and direct manner to the sit-ski to facilitate good control. The position of the weight of a motor might be favorable in the rear, considering to easily maneuver out of groomed tracks, but that statement needs to be tested additionally with end-users.

Chapter 5

Design Function – Drive System

One of three design functions the development of the motorized sit-ski was divided into, was the drive system, which is covered in this chapter. In the context of the thesis, the term the drive system refers to what can be understood as the *propulsor* in the propulsion system; the tire or continuous track, in addition to the hub motor and drive wheel. In automotive engineering, the term might also refer to the battery and control system, which is not the case in this paper. Considerations and reasoning concerning the motor of choice are described in section 7.1 and not in this chapter.

The drive system was considered the most differentiating design function developing a motorized CCSS and was in focus from the beginning. The development of the drive system was crucial to the progression because it provided the forward motion aiding the skier with propulsion. The system transmitted power from the motor to the snow by transforming motor torque into tractive force. Being crucial, the drive system defined boundaries for the rest of the sit-ski design. Dimensions of the power transmission system determined how the chassis could be constructed.

Utilizing the power provided by the motor in an effective way to achieve propulsion deals with some of the challenges presented in chapter 4 Design Challenges. While supplying sufficient power to aid the skier, the drive system should not contribute too much to the weight of the CCSS, as it would cancel out the provided power. It was therefore considered important to keep the system at a fairly low weight, as stated in section 4.5. To be a useful device it should work in multiple snow conditions without destroying the groomed tracks. Considering production and further development, the system should consist of standardized parts making assembly and building efficient as described in section 4.9.

An especially important challenge was to provide enough friction against the snow, described in section 4.2. The amount of traction necessary to assist with propulsion, and subsequently how to accommodate enough normal force on the drive wheel, were big questions that needed answers initially. The task was complex since precautions were needed in the ski trails. The issue of propulsion could have been effectively solved with a heavy motorized track system, but that would not have satisfied the skiers destroying the ski tracks for other users.

As described in section 4.2, based on equation 4.4, the maximum tractive effort increases with contact area A between the drive system and snow surface. Hence, the drive system should be designed to increase the contact area, by increasing wheel diameter and width or length of the track. However, increasing the diameter of the wheel also negatively influences the drive force, as shown with equation 4.2 in section 4.1.

The morphological box in figure 5.1 show some general ideas regarding the design of the motorized sit-ski, with four examples of solutions for each sub-function. Displayed solutions for the functions vary in detail and relevance, but are results of an initial ideation phase in the thesis work, showing some aspects of the development and how wide the solution space was.

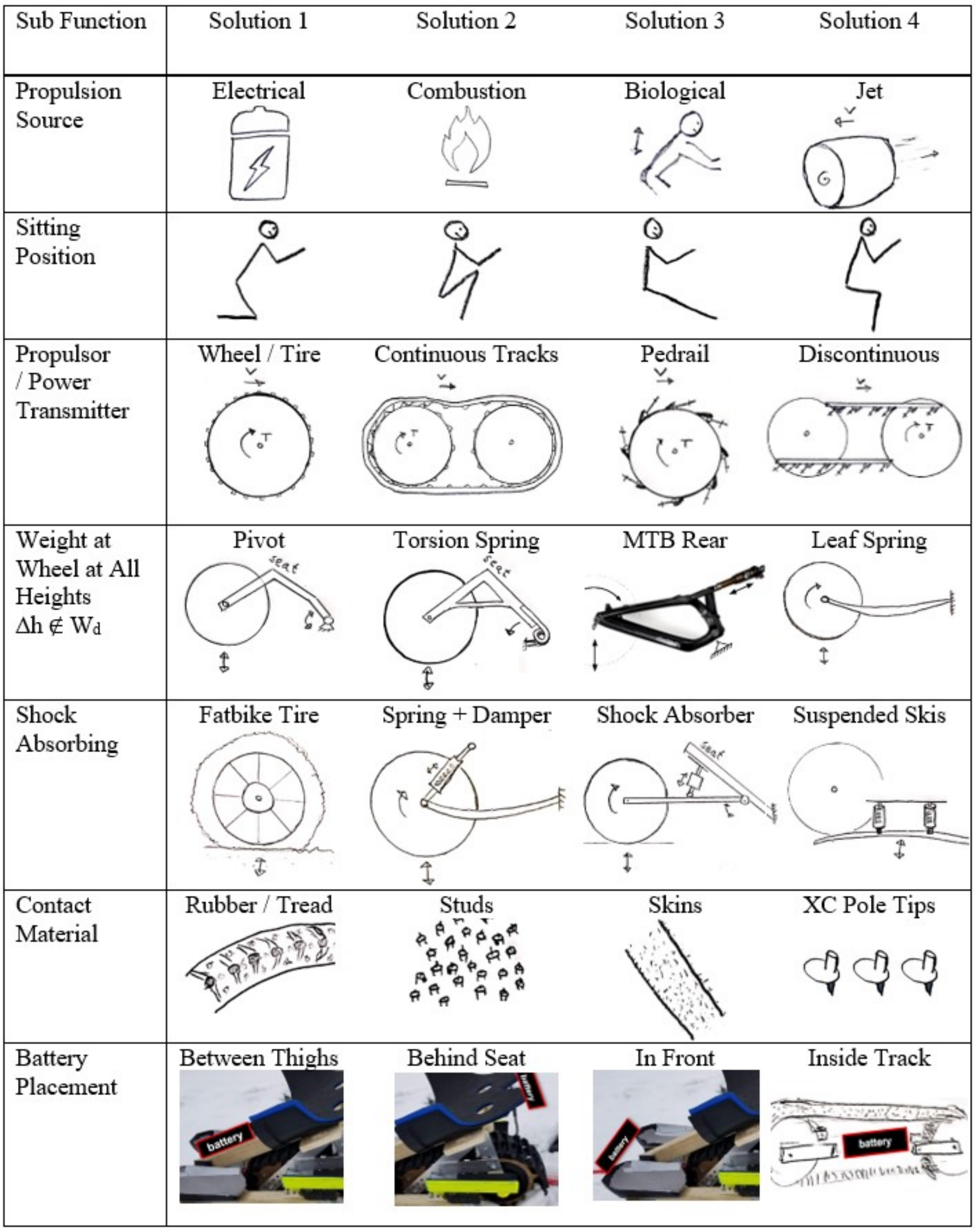


Figure 5.1: Morphological box with solutions related to the drive system.

Section 3.3.2, describes how the fidelity of prototypes was taken into consideration when the tests were evaluated. In-house developed and manufactured parts experienced lower prototype fidelity than the commercialized wheel that was tested. The fatbike wheel was a fully developed product and a working part of the full-body prototype. As the testing with the fatbike wheel was intended to assess the functionality of the drive system, the test result would not have been influenced much from the fidelity. However, the drive system of the prototype with a small wheel was in-house developed and did hence experience lower fidelity, which was also the case for the rubber track prototype. For the continuous track being a complex system, the fidelity was relatively low and therefore influenced the test results more. All drive system prototypes utilized the same type of hub motor with the same power and rolling resistance.

Initially, the drive system concepts were divided into two conceptually different alternatives; wheel or track. Wheel solutions were further divided into a set of diameters, and the sections of this chapter are classified in the same manner. Additional investigated and varied parameters – related to the contact surface of the drive system – were contact area, material and tread pattern.

5.1 Small Wheel

To provide propulsion, a small wheel surrounding the hub motor was a solution investigated. A small diameter facilitated a position of the drive system underneath the skier. The center of the wheel was because of the small radius close to the trail and the wheel did not change the center of gravity for the total system too much. Instead, the net weight of the motor contributed to keeping the center of gravity low which was presumed important.

A disadvantage of a small and solid wheel was a reduced contact area. Being solid, the contact area was theoretically only considered as a narrow line. In reality, the contact area would be somewhat larger as the wheel was pushed down and deformed the snow surface, but the contact area would still be quite small. Since the radius is small, the wheel's angle of attack would be quite large. The force would not only work in the desired direction but also downwards causing the wheel to dig down more easily.

Aspects of the concept of a small drive wheel are given in section 5.1.3.

5.1.1 Development

It was desired to start testing of the wheel concept and drive system early. Testing would provide knowledge about the ski tracks; showing characteristics of the snow surface the motor power should be transmitted to. The wheel concept was less complex and demanded fewer resources to build and was therefore chosen to be explored first.

A small wheel would lead to a shorter arm from the pivot point and therefore more weight on the wheel. As the amount of normal force desired on the drive system was still unknown, it was considered beneficial to explore a smaller wheel first. Greater normal force contributes to the tractive force and is described in section 6.1.3.

To investigate the wheel concept, a wheel with a small diameter was made. The model was made by laser cutting MDF-plates that were fastened directly to the motor. The discs were made as small as possible with a diameter of 20 cm. The spoke holes on the brim

Figure 5.2: The initial small wheel prototype.

of the motor was used to attach the discs. The MDF-discs were 6 mm thick and the wheel was made by layering or stacking them to achieve the desired width.

The first proof of concept model of the wheel had a surface width of roughly 3 cm with discs only mounted in the center of the motor. The wheel was covered with skins and a studded bicycle tire enabling tests of different surfaces.

As the first small wheel prototype was found to be unstable, more discs with the same diameter were cut and added to make the wheel wider. The same attachment method was used to fasten the discs on the outside of the motor. The added discs built the width to 9 cm. The maximum width of the higher middle of the ski track was supposed to be 10 cm and the width of the motor did not exceed this. The discs added some weight to the wheel, but the greatest contribution to the weight of the drive system was still the motor itself, in addition to the battery.

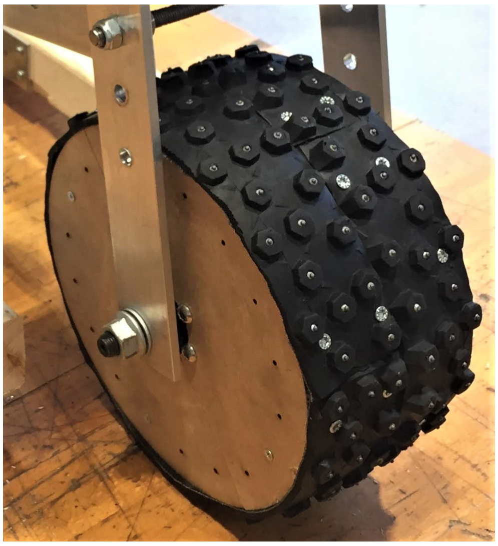


Figure 5.3: The second iteration of a small wheel with increased width.

A studded bicycle tire was used as the surface of the wheel. The tire was cut and fastened to the wheel with screws, keeping the tire in place during testing.

5.1.2 Test Results

The prototypes of the small wheel were tested in a variety of snow conditions, followed by important learning points. The initial model worked as a proof of concept prototype and the results were considered binary, showing either a plausible solution or not. Much wheelspin and lack of grip were experienced, a result not being satisfactory, but the model still showed signs of preferable functionalities.

To investigate the solution further, the second wider model was also tested. The small wheel showed great results on solid snow conditions with the drive system able to provide sufficient propulsion and good acceleration. On loose snow conditions, however, the wheel struggled to uphold the propulsion and started to slip, dig down and destroy the ski trail. The lack of grip in looser conditions might be blamed on the not particularly suitable tread pattern. On this prototype, the tread had studs, but the rubber had no snow relevant grousers and was more suited for icy conditions. Additionally, with the drive wheel right under the seat, an uncomfortable low degree of shock absorption was experienced.

Descriptions of the tests performed on the small wheel prototypes are presented in Appendix A.

5.1.3 Evaluation of the Concept of a Drive Wheel with Small Radius

	Advantages
+	Small radius increases the drive force F, given constant motor torque
+	Lower weight
+	Occupying less space (compared to frame and user, regarding positioning)
+	Lowering center of gravity
+	Low rolling resistance for wheels

	Disadvantages
÷	Small contact area reducing coefficient of traction μ_t → not sufficient drawbar pull F_d in averagely loose conditions
÷	Much wheelspin and stress on snow → destruction of ski trail

Table 5.1: Aspects of a Drive Wheel of Small Radius.

5.2 Big Wheel – Fatbike Tire

The concept of using a wheel as the drive system was not limited to a small wheel as a larger wheel radius also could have some beneficial properties that were worth exploring. Big diameter facilitates big contact area, especially with less inflation and lower tire pressure. This is beneficial for the traction and vital for the functionality of the motorized sit-ski. A larger wheel would have a more acute angle of attack causing the force to mainly work in the desired direction.

A larger wheel also enabled the use of a commercially available bicycle wheel of 26". As described in section 4.9, standardization was a challenge to solve and the use of commercial parts would contribute to easier manufacturing. The bicycle wheel being commercial also made it convenient to test with limited development needed.

Increasing the wheel size, however, elevated the center of gravity and made the sit-ski less stable. Because of its size, the wheel could not be positioned underneath the seat and had to be moved behind the sit-ski. With the center of gravity elevated and moved back, the handling of the sit-ski became different and could be experienced difficult.

The increased wheel size and the same amount of torque delivered from the motor led to less drive force than a wheel with a smaller radius, which is further described in section 5.3.

5.2.1 Development

As the wheel was commercial, almost no development was needed. Only small changes to the suspension of the chassis to attach the wheel were made. The contact area of the wheel was adjusted using the air pressure.

Figure 5.4: The commercial fatbike wheel connected to the chassis.

5.2.2 Test Results

Experienced in the testing of the concept was sufficient grip, almost no slip and close to no destruction of the ski trail. Simultaneously, the drive force and drawbar pull were low at low velocity. Not much assistance was provided to the DP standing still, but after a push to get started, the drawbar pull was sufficient to maintain high velocity. Seen in figure 6.5 is the version tested, the prototype with a 26" wheel with fatbike tire – which was experienced to be relatively heavy. A high center of gravity resulted in an impression of instability and risk of the device tilting to the side. A subjective feeling was that the prototype provided a pleasing amount of shock absorption being comfortable. It was believed that the fatbike tire and the wheel being positioned behind the user, were the cause for the shock absorption being better than the prototype with the small wheel. Another parameter to be included in the consideration is the reduced normal force W_d due to chassis design and big wheel.

The two test persons reported satisfactory results for the drive system, though the drive force should have been higher. The improvement point of most interest was, therefore, decreasing radius.

A description of the test performed can be read in Appendix A, date 24.03.2020, Test 1.

5.2.3 Evaluation of the Concept of a Drive Wheel of Large Radius

	Advantages
+	Sufficiently big contact area and coefficient of traction μ_t
+	Low rolling resistance for wheels
+	Facilitate high longitudinal velocity of the vehicle
+	Standardized bicycle wheels provide good access and price reduction
+	Acceptable destruction of the ski trail
+	Relatively few parts that can break

	Disadvantages
÷	Big radius reduces drive force F provided by motor torque
÷	Comparatively heavy weight
÷	Occupying more space (compared to frame, so it cannot be positioned close to the user or pivot point)
	→ Center of gravity of the entire vehicle being moved backward
	→ Hard to facilitate more normal force W_d
÷	Higher center of gravity

Table 5.2: Aspects of a drive wheel with a big diameter.

5.3 Wheel of Intermediate Radius

From the development and testing of the small and large wheel, both solutions showed some advantages and flaws. A compromise between the good traction of a big wheel and drive force of a small wheel might be available with a wheel of intermediate radius. Sufficient contact area is important considering the coefficient of traction and destruction of the ski trail. Simultaneously, the radius should be sufficiently low compared to the motor to maintain a pleasing drive force uphill. In such a way, a bigger motor will not be needed.

Considering a more preferable diameter, it should be somewhere in between the two diameters of the wheels tested;
– an 8" diameter wheel that experienced much drive force and acceleration on icy conditions, but lack of traction, wheelspin and destruction of the ski trails in average snow conditions.
– a 26" diameter wheel with fatbike tire that experienced bad starting acceleration, but high velocity on the flats, and sufficient traction and low degree of ski trail destruction on average snow conditions.

→ A diameter that corresponds with available commercial wheels for bicycles; 16" – a radius of 20.3 cm – could be a standardized part close to optimum.

The wide fatbike tire was assumed to be preferred – a solution that facilitated a big contact surface and a beneficial tread pattern, so the coefficient of traction should be sufficient. From the tests, the fatbike tire showed good results.

5.3.1 Calculations on Radius Based on Motor Torque

From equation 4.2 for drive force, $F = T/r$, estimations for the needed radius can be made, assuming the torque from the standardized bicycle motor is constant. Estimating the tractive force F_t with the drive force, one can use Newton's second law to calculate the maximum radius allowed.

$$\sum F_x = ma = F_t - mg \cdot \sin\alpha - R. \quad (5.1)$$

Assumptions needed are no slip or infinite grip, motion resistance $R = 0$ and no energy loss in the system, given the torque of the motor. Mass of the system m includes both user and the motorized CCSS. The maximum radius allowed to accelerate or maintain constant velocity in uphill of gradient α can then be estimated. Calculated in Matlab, the resulting output radius is displayed in figure 5.5.

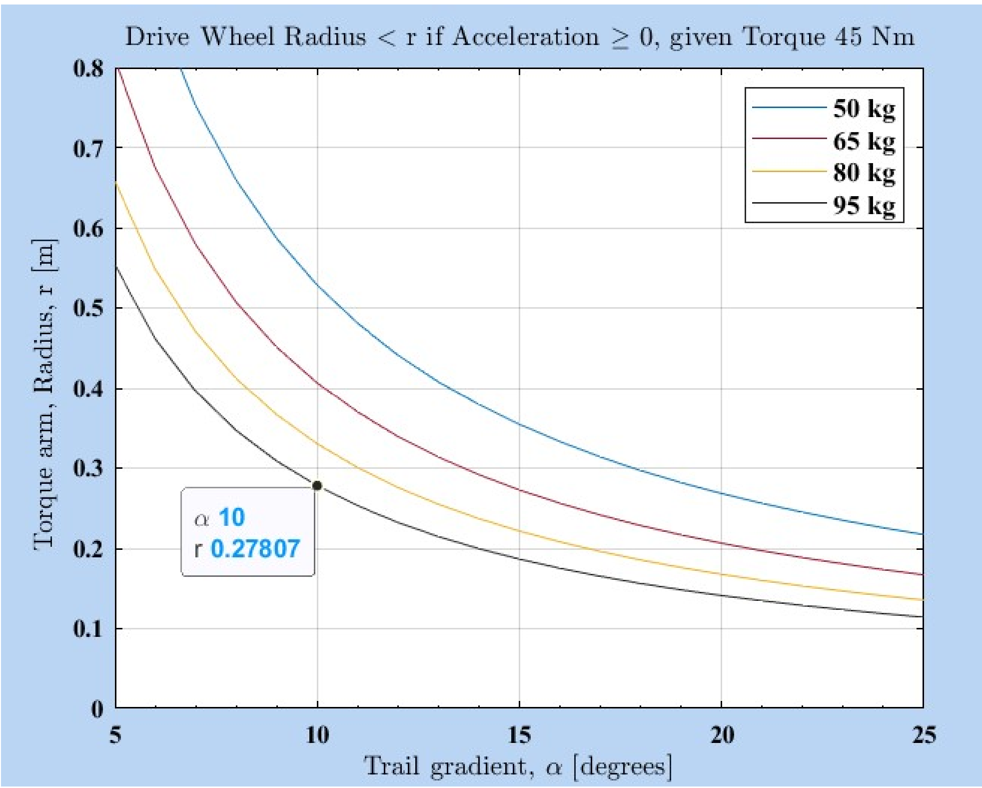


Figure 5.5: Graph of radius with respect to gradient and mass of system.

To show a numerical example from the plot, the values of a point on the graph for 95 kg mass on the system are displayed – a weight corresponding to a heavy user. Given a climb gradient of 10° and motor torque T = 45 Nm; if the motor should self-assisted drive the sit-ski uphill, the radius is required to be lower than 0.278 meters – a diameter of about 22". This corresponds to a drive force

$$F = 162\ N. \tag{5.2}$$

With an estimated contact area $A = 0.01$ m^2 and normal force on the drive wheel $W_d = 400\ N$, in addition to the cohesion and friction angle given in section 4.2, (Sweden)[37]; $c = 6\ kPa$ and $\phi = 20.7°$ – the force the snow can withstand can be calculated with equation 4.4:

$$F_{max} = cA + W_d\ \tan\phi = 6\ kPa \cdot 0.01m^2 + 400\ N \cdot \tan 20.7° = 211\ N$$

For $c = 1.03\ kPa$ and $\phi = 19.7°$ (U.S.)[37], the maximum force would be $F_{max} = 154\,N$.

These two numerical examples of F_{max} is approximately within the same range as the drive force, so it might be reasonable to assume no slip as it simplifies the model. At least these calculations imply a limited degree of slip or acceptable destruction of the ski trail. However, $0.01m^2$ is a relatively high contact area for tires, so the inflated tire pressure must be fairly low and fatbike tire would be desired. The tread pattern should also be beneficial.

Evaluating the two prototypes tested with 8" and 26" diameter drive wheel, one can calculate the theoretical drive force to compare the values to F_{max} or verify the statements above. With the same torque on 45 Nm, the drive force would have been approximately $F = 450\ N$ with the small wheel and $F = 135\ N$ with the big wheel. This can be reasonable compared to test results, as the small wheel exceeded the shear strength of the average snow, resulting in much slip, while the big wheel did not destroy the ski trail.

The snow conditions will vary greatly, so the material parameters showed for the snow is to work as an example. In general, there are many assumptions and much uncertainty present. The calculations and numerical values should hence be interpreted qualitatively.

The propulsive effort of the user DP is not included in the equations, which would be the case for the application of the motorized sit-ski. The output radius and forces should be interpreted thereafter, so a bigger radius could be accepted since the device is only to count as assistance. At the same time, motion resistance and some degree of slip will be present, reducing the effect of the provided power.

The necessary torque given a radius of 20 cm of the drive wheel is displayed in figure 7.3 in chapter 7. The graph is based on the same calculation from Newton's second law and drive force.

Normal force W_d estimations can be seen in section 6.1.3; calculations taking weight distribution into account with a pivot point. Numerical values for 50 % of the weight on the seat is presented for the two chassis prototypes of small and big wheel. The calculation in this section assumed $W_d = 400N$, which might be optimistic, but in between the estimated normal forces for the two previous wheel prototypes.

5.3.2 Evaluation of the Concept of a Drive Wheel of Intermediate Radius

	Advantages
+	Sufficient traction
+	Standardized and legal electric-bike motor will be satisfactory
+	Neat
+	Idea looks best on paper
+	Compatible with fatbike tire

	Uncertainties
÷	(No significant disadvantages)
±	Intermediate to low degree of destruction of the ski trail
±	Intermediate weight
±	Standardization
±	Center of gravity
±	Occupying intermediate amount of space

Table 5.3: Theoretical aspects of a drive wheel of intermediate diameter.

5.4 Rubber Track

The concept described in this section consists of a drive system with a continuous track made of reinforced natural rubber. Physically realized was a prototype with a rubber track from a snowblower. Two sprocket wheels working inside the track was a neat and convenient solution to the problem.

The most important benefits of the concept were a big contact surface and a tread pattern beneficial for snow. The pattern in the rubber can be associated with grooves, a design used for soft contact surfaces. To supply sufficient tractive force and drawbar pull to the user, good grip and enough traction is a must. As described in section 4.7, a larger contact area will increase the tractive effort and in turn increase the drawbar pull. Additionally, an increased contact area will reduce the destruction of the ski trail, an important design challenge described in section 4.3. As of equation 4.3, for snow with significant cohesion, the shear strength of the ski trail will increase with the contact area. Stated in section 4.2.1, a drive system with a continuous track instead of a tire was reasonably assumed to have increased coefficient of traction, less slip and increased rolling resistance. [39][38]

As the optimal track tension and seat height were unknowns, the length of the suspension aluminum bars were made set-based, so it could be adjusted during assembly. For instance, the shaft could be placed in different screw holes. Shaft-to-shaft length could be adjusted with the strut bar, as implied by figure 5.8. Requirements of design specifications were set as ranges, not points. The placement of the track relative to the snow, and sinkage, were also unknowns. Other alternatives to adjusting shaft-to-shaft length can be seen in the morphological box in figure 5.9.

Aspects of a drive system design with a rubber track are displayed in section 5.4.3.

Figure 5.6: The first prototype with rubber track in action.

5.4.1 Development

For the prototype, the continuous rubber track was bought separately from a snowblower retailer, so the drive sprocket was designed in-house to make fit on the outside the hub motor. Efforts were made to make the sprocket fit inside the default track – a standardized track that had no written specifications. Manual measurements and varying actual pitch for the different teeth inside the track did not simplify the task.

To resist disturbance from snow, ice grains and other external elements getting inside the track, the tooth design is of importance. Consequently, it was desired a big tooth height of the rubber track and sprocket, in addition to the tooth thickness being smaller than the space width between the teeth. Not as for timing belts and drive belts used in indoor machines and automotive industry, where teeth of belt and wheel fit perfectly with no gap designed – an application with higher desired track tension.

In general, tooth pitch is required to be the same for sprocket and toothed belts or tracks.

$$\text{Circular tooth pitch} = \frac{\pi \cdot diameter}{\#teeth}$$

Since the number of teeth must be an integer and the pitch should be the same for sprocket and track, the diameter of the sprocket wheels were designed thereafter. The diameter of the two wheels relied on the track length, but measurements of the length were considered as an approximation. The default sprockets used in the commercial snowblower were heavy and not fitting the motorized sit-ski in size. The diameter of the hub motor was larger than the diameter of the default sprockets. Hence, the drive sprocket got a diameter increase corresponding to two teeth, resulting in the second wheel getting a diameter decrease corresponding to two teeth.

Figure 5.7: To rapidly make a sprocket wheel in exact dimensions, MDF-plates were laser cut and assembled on two parallel bearings.

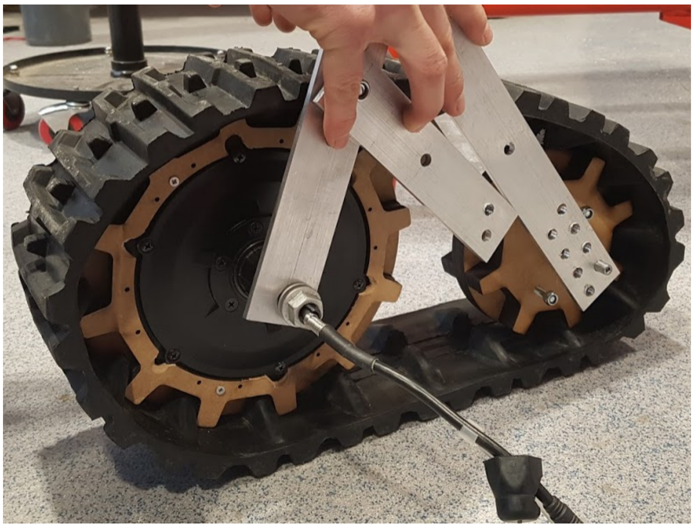
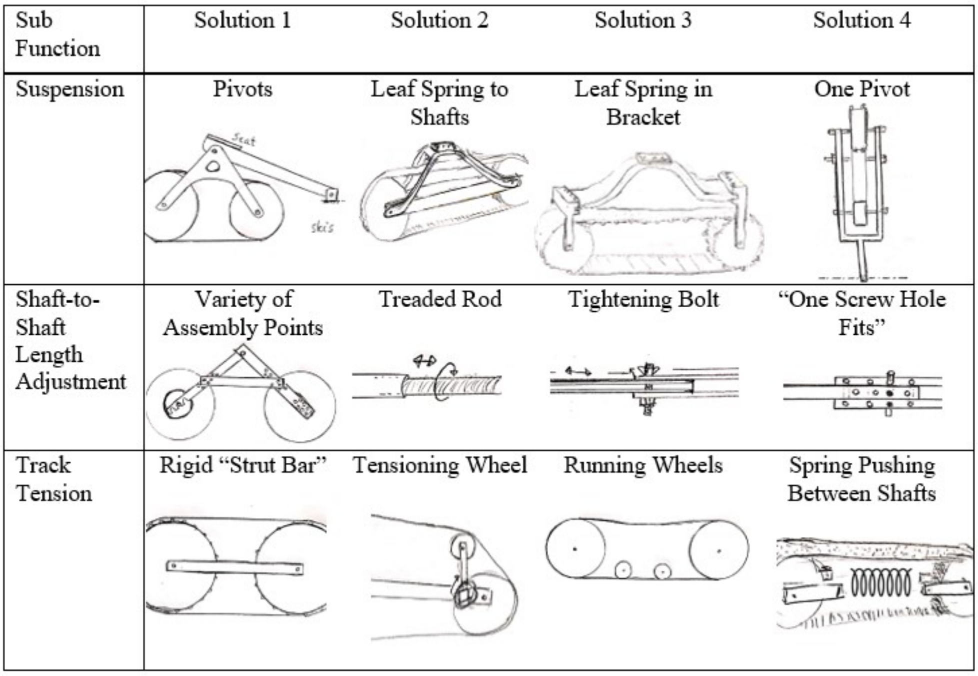


Figure 5.8: Assembling the drive system of the first track prototype -— a set-based prototype with adjustable length of suspension bars in aluminum.



Sub Function	Solution 1	Solution 2	Solution 3	Solution 4
Suspension	Pivots	Leaf Spring to Shafts	Leaf Spring in Bracket	One Pivot
Shaft-to-Shaft Length Adjustment	Variety of Assembly Points	Treaded Rod	Tightening Bolt	"One Screw Hole Fits"
Track Tension	Rigid "Strut Bar"	Tensioning Wheel	Running Wheels	Spring Pushing Between Shafts

Figure 5.9: Morphological box regarding a prototype with continuous track.

The morphological box in figure 5.9 show some additional solutions connected to the track suspension, considered in the ideation phase of the development.There are some solutions not described in this section that are possible to implement but considered as not beneficial to the prototype. Solution 1 in the left column was chosen for the three sub-functions displayed in the box.

Combined with sufficient track tension, the assembly of the continuous track onto the wheels was a challenge of the design. While the solution chosen for the first proof of concept prototype was supposed to be rapid and simple, it had to function expediently. No fancy details, but keeping it as simple and cheap as possible, before one concept was chosen. Hence, the solution functioning best theoretically, might not be preferred for the first prototype. No running wheels, tensioning wheel, shock absorbers or coil springs were implemented in the first iteration. A reason for not using a coil-over shock absorber was that most commercial available versions would be too big and therefore not convenient to implement in the sit-ski design. As described in section 4.6, the design space was limited, in addition to weight minimization described in section 4.5.

The required track tension turned out to be fairly low, so mounting the wheel shafts onto the assembly points of the suspension, was manageable with human power and no technical solution. A variety of assembly points were machined and drilled in the aluminum bars to simplify the process of adjusting track tension and seat height. A physical version can be seen in figure 5.8. One can say that a rigid strut bar was utilized with a range of assembly point options to vary the length from shaft to shaft. The shaft inside the front wheel sprocket seen in figure 5.7, was machined with a lathe.

Figure 5.10: Half of the drive wheel sprocket printed to fit outside the hub motor with printing layer direction to resist shear stress from acting forces.

The continuous track only used two wheels and the location of the drive wheel was relatively easy to decide, as it only could be positioned in the front or rear of the continuous track. As having the drive wheel in the rear would pull the bottom part of the track – making the part of the track in contact with the snow in tension – it was the motor location of choice. The drive wheel with the hub motor inside would also be bigger than the other wheel, requiring more space. Since it was a limited amount of space beneath the user, having the smaller wheel in front would be convenient.

5.4.2 Test Results

The first prototype with a rubber track was tested and assessed as a concept. As mentioned in section 3.3.2, the concept results were influenced by the fidelity of the prototype. During the second test, the prototype got several parts broken. The new improved prototype with higher fidelity was not finally realized and therefore not covered in the test results.

The test description can be seen in Appendix A, date 09.03.2020.

It was experienced good traction for the prototype with a continuous track. No slippage occurred, but the mark left on the snow was significant as the grousers of the tread pattern had an indentation depth of about 1 cm. What was considered a significant disadvantage, was the substantial motion resistance. The rolling resistance was high, especially with the motor turned off. A reason for the high motion resistance could possibly be blamed on the low fidelity, but since an improved prototype not was made, it remained unknown. The prototype was also experienced as relatively heavy.

5.4.3 Evaluation of the Concept of Rubber Track

	Advantages
+	Large contact area and coefficient of traction μ_t
+	Limited destruction of the ski trail due to big contact area to the snow
+	Grousers and rubber pattern relevant for snow conditions
+	Not depending on grooming of trails
+	Facilitate low center of gravity

	Disadvantages
÷	Low efficiency. Much power loss in the transmission from hub motor to track
÷	Much motion resistance, also with motor turned off
÷	Heavy weight
÷	Many moving parts → more can go wrong or be destroyed
÷	Manufacturing more demanding with high level of detail
÷	Few standardized parts → expensive
÷	Relatively much noise

Table 5.4: Aspects of a CCSS with Rubber Track.

5.5 Belt with Attached Skins or Friction Layer

The industry has experience with attaching several types of materials to belts; spikes, sticks, glued surfaces, grousers, etc. The applications vary, but of interest in this context are for instance conveyor belts constructed to move items such as luggage, waste materials and minerals. Customization opportunities for the contact material do not have many limitations.

The purpose of the concept presented in this section – as opposed to tires or continuous tracks used in other vehicles driving on snow – is that the destruction of the groomed ski tracks should be minimized, and prioritized as the most important design parameter. The idea of a long customized belt might be the best option considering the design challenge described in section 4.3, destruction of the ski trail. With a big contact surface and no grooves or deep tread pattern intending marks into the snow, the solution of customized tracks can be beneficial. For instance, one can see from the print left by skis with attached skins, the destruction is minimal and distributed evenly over a larger area.

No conclusion was made on how the customization of a track should be optimized. The intended solution consisted of a timing belt with attached skins. Width of the belt should correspond to the raised middle of the groomed ski track. Length of the belt should be long compared to the CCSS – about two meters – facilitating the placement of battery within the belt to lower center of gravity. Attached skins would be of the same type as used in ski touring, which was available in regular sports shops.

5.5.1 Investigation

To investigate the potential of attaching skins, a simple prototype was constructed, after reading background material. Skins were glued onto a small wheel. The assessment was not comprehensive, but gave insight into the challenges of the concept, keeping in mind that skins require bigger contact surface to function optimally.

Research on skins was conducted regarding the coefficient of friction and showed large variation of values for friction in the direction backward and forward. For instance, the skin *Pomoca Free Pro* with a composition of 30% Nylon and 70% Mohair was found to have a coefficient of friction for slide $\mu = 0.258$, and a coefficient of friction for grip $\mu = 2.56$. These numerical results are believed to rely on the snow condition. [41]

Considering the coefficient of friction for skins, the concept looks good on paper. With the big difference in friction backward and forward, the greatest disadvantage for rubber track could be minimized. Inspired by the sport of ski touring and XC skiing – where skins are widely used – it was believed that the destruction of the ski trail could be kept at a minimum.

Influenced from industry, solutions of continuous rubber belts were investigated. However, the application differs for outdoor propulsion systems and stationary indoor machines, where weight reduction has not been a prioritized matter.

Friction drive rubber tracks exist for outdoor use, but is not similar to timing belts in engines and machines. For the application of the drive system for the motorized sit-ski, it was concluded that the friction would not be sufficient in the snowy conditions – the assumed low fidelity of the prototype would complicate the construction of a system with required high belt tension.

Figure 5.11: Skins attached on a drive wheel, after experiencing wheelspin.

The testing resulted in the skin hairs changing direction, losing its beneficial properties after experiencing repeated full slip with the weight of a user applied. Based on limited material, a decision was made — that the concept of skins had less potential and would not be worth the resources needed at this point. Further development could wait.

5.5.2 Evaluation of the Concept of Customized Track with Added Friction Material

	Advantages
+	Facilitate minimum ski trail destruction
+	Several belt dimensions available, making customization simpler

	Disadvantages
÷	Might be heavy
÷	Novel concept as there are no similar commercial products → high risk of failure during the development
÷	Timing belts and similar are not designed for environments with the risk of snow getting between sprocket and belt

Table 5.5: Aspects of the concept of a customized track.

Chapter 6

Design Function – Chassis Design

Regular cross-country sit-skis consist mainly of the frame with some ergonomic variation in position and amount of padding. The frame supports the skier, keeping them upright and set the sitting position. The chassis designed in the thesis integrates with all other parts and connects all the functions. This means the chassis also had a different objective, supporting the drive system.

The main function of the frame is still supporting the skier and determine the sitting position. However, being a motorized vehicle, supporting the drive system is an additional important function. The chassis works together with the drive system to distribute the weight from the skier to the system. The project aims to make a complete product instead of making the propulsion an extra feature that could be attached. The implementation of the drive with the chassis, therefore, had to be executed beneficially.

The drive system imposes some limitations on the design of the chassis. The frame and suspension needed to accommodate the drive for the device to work properly. Restrictions that are usually not present in the design of the CCSS frame had to be taken into consideration. The concepts of the chassis design, therefore, focus on providing sufficient weight to the drive wheel.

Although the main purposes were in focus, the other design challenges connected to the frame design were not ignored. The chassis of the motorized sit-ski contributes to the total weight, so weight should be considered in the design. At the same time, the sit-ski needs to be quite stiff not to lose power provided from the skier double-poling.

As the motorized sit-ski is supposed to be used by a wide user group with different needs, it should be adjustable. The adjustment possibilities and providing a correct sitting position are some of the main attributes of a regular amateur CCSS. At this stage of development, however, adjustment possibilities were not considered crucial and hence designated less focus.

The models developed in the thesis was only facilitating one sitting position, a knee-standing position. The sitting position was chosen because it was considered to allow more options for building and external constructions. A knee-standing position favors lower injuries and the skier is enabled more movement of the upper body that would be beneficial when testing the application. One could argue that a neutral sitting position should have been used to facilitate more users to test at an earlier stage, but in the initial stage, the extra allowed movement was considered to benefit the process more. After the main concept has been made and investigated, the different sitting positions should be evaluated to cover the user group in total. The knee-standing position and the other sitting positions are described in section 2.7 in the pre-master in Appendix B.

The height of the drive system follows the groomed track. Given the difference in height inside and outside of the classic ski track, the position of the drive system compared to the base of the skis will vary accordingly. Therefore, the sit-ski needs to be able to change the height of the propulsion system as the height of the ski track varies as shown in figure 4.2. The snow conditions will also affect the track height, as shown in figure 4.3. When the sit-ski is working in the groomed track, the height difference between the drive wheel and skis will be about 5 cm, as described in section 4.8. However, skiing in the trail outside the track, there will be no height difference. Hence, the suspension must facilitate a low difference in normal force W_d due to traction, as well as making it comfortable for the user.

It should be noted that the concepts have one essential difference. They do either have a fixed or dynamic seat position. Whether the sit-ski has a rigid or moving sitting position is crucial for the user regarding DP and training. A moving seat is not allowed in competitions, so professional athletes are assumed to be excluded from the user group with a pivot point chassis design.

Focusing on the distribution of weight to the drive system, this chapter presents different concepts to the Chassis Design in each of the following sections. A solution that easily enables development and testing of the drive system was explored to a greater extent. This chassis concept contains a pivot point by the knees and was the only concept physically realized and therefore presented first. The additional concepts have not yet been developed or tested.

6.1 Moving Sitting Position – Pivot Point by Knees

A concept of the chassis design aiming to provide sufficient weight to the drive system utilizing the user's weight. By using a pivot point in the same position as the knee joint, the seat of the user would move with the seat of the CCSS, and the weight of the user's upper body would be transferred directly to the drive system. The normal force W_d on the drive system depends on the position of the user and changes if the user leans forward or backward, shifting the center of gravity.

The pivot point allows the drive system to travel in the z-direction and follow the height difference of the groomed track while distributing enough weight to it. The sitting position, connected directly to the drive wheel, will depend on the surface of the ski trail. A change in the height of the track, e.g. changing in and out of the grooves of the ski track made for classic skiing, would change the sitting height equally.

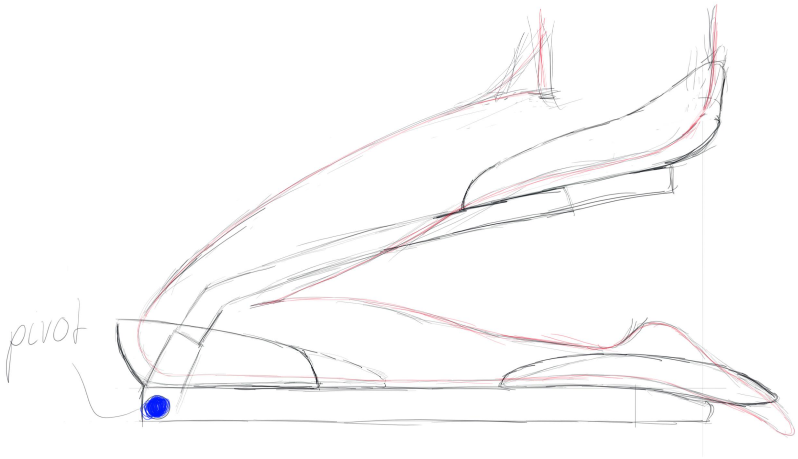


Figure 6.1: Side view sketch of the chassis with a frontal pivot point.

Inserting a pivot point at the knees was considered an easy way to provide sufficient weight onto the drive and chosen to aid the investigation of the drive system. This concept was considered less complex and easier and therefore quickly built as a prototype to facilitate testing of the drive system.

6.1.1 Initial Prototype

The first prototype was made to test the drive system quickly. The initial prototype served as a proof of concept prototype to investigate how a pivot in the front transferred and distributed the weight from the user to the drive system. It also enabled testing of the motor strength. To test the drive concept of a hub motor in a small wheel, an adjusted version of a previous CCSS prototype from the pre-master work was used.

Using the chosen concept for the chassis, a frontal pivot point was introduced to the old rigid model, enabling the transfer of weight onto the drive system. The model had a bottom frame in the form of a capital H, not allowing the drive to be positioned directly underneath the skier. Instead, the drive was positioned behind the sit-ski. Suspension supporting the drive was attached underneath the seat in the form of aluminum bars. The fidelity of the prototype was low and the construction was unstable.

Figure 6.2: An initial prototype with an H-shaped bottom frame.

The test of the initial prototype of the chassis resulted in learning points. During the first quick test, the wheel would not remain in the center of the track between the skis, partly because of the unstable construction.

As a means to investigate how the magnitude of force provided to the drive system changed the traction, a different test using the initial prototype was conducted. The prototype was adjusted and made rigid. Instead of fastening the drive to the suspension that transferred weight from the user, an extension from the frame was used. The extensions were unstable but considered sufficient to gain empirical results based on how the amount of force influenced the grip.

The test was conducted by applying weight with varying distance to the drive wheel. The normal force W_d changed by varying placement of the weight on the extensions the drive wheel was connected to – changing the length of the arm. The test is briefly described in Appendix A, date 12.02.2020, Test 2.

Since the testing was focused on the normal force W_d on the drive wheel, it was considered as a part of the chassis design and not the drive system. Though the test delivered empirical results, it was beneficial to get a picture of how much the difference in the normal force W_d affected the grip and drawbar pull.

Figure 6.3: Chassis made to investigate magnitude of force required on the drive.

6.1.2 Set-Based Prototype

The initial prototype had shown the plausibility of a pivot point to distribute weight to the drive system. It was however not made with the drive system in mind and the interaction between the drive and chassis was not favorable. As the overall idea was to develop a sit-ski with the motor fully implemented and not as an accessory, the chassis should be built around the drive system contributing to the aspired function.

A new prototype of the chassis was planned and made to interact better with the drive system using the idea of a pivot point in the front to transfer the weight onto it. The model should facilitate testing of the different drive systems. To allow testing with different drive systems, the building of the chassis prototype used the principle of set-based prototypes.

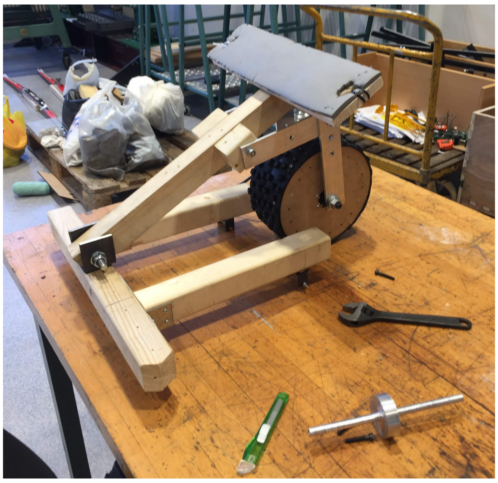


Figure 6.4: Set-Based prototype of the chassis with an open square bottom frame to facilitate the use of a center positioned motor.

The bottom frame on the new prototype was built as an open square – instead of a bottom center beam – to better facilitate the use of a center positioned motor. As the initial prototype, it was made of wooden materials. The diagonal beam was connected to the bottom frame with a self-made hinge working as a center pivot point placed on the short perpendicular rod. The pivot point allowed for rotation giving the seat post a small movement.

By implementing interchangeable parts, the prototype enabled testing of multiple solutions with a few easy changes. This was done by having multiple fastening mechanisms for the suspensions. The prototype utilized different suspensions attached to the diagonal beam that fit the different concepts of the drive systems; small wheel, big wheel and continuous track.

The fidelity of the prototype was still quite low, causing the construction to be a bit unstable but Compared to the initial prototype, the new prototype was far more robust and solid. The hinge working as a pivot point was considered a weak point in the construction. At this stage of the development process, the fidelity was considered sufficient.

Figure 6.5: The chassis prototype with a different drive system, big wheel with fatbike tire.

Between tests using the prototype, small or larger adjustments were made to alter and strengthen the construction if necessary. These adjustments were considered small iteration within the prototype. Some of the changes of the chassis between tests were conducted to facilitate testing of the different drive systems as seen in figure 6.4 and figure 6.5.

A new improved prototype made of aluminum was under construction, fixing the unstable diagonal beam by making a better pivot point. Instead of using the hinge, a water cut aluminum part was ordered from the workshop. The pivot point was lowered as the water cut part was meant to revolve around the perpendicular rod making up the front of the open square. Moving the pivot point lower would influence the rotary movement of the diagonal beam, but it was considered more crucial having a robust pivot point for the prototype.

Figure 6.6: New bottom frame.

6.1.3 Calculations

This section will present the influence of the chassis design geometry on the normal force W_d with some theoretical calculations.

Calculations with free-body-diagram, FBD, in two dimensions were used to compare the prototypes of the chassis designed for small wheel and big wheel. The resulting normal force W_d on the drive wheel of the two drive systems could be compared to the corresponding friction required to provide propulsion uphill.

The magnitude of the numbers should be interpreted qualitatively, only as an indication, to show the consequence of motor placement relative to the pivot point. The chassis design has a significant influence on the normal force W_d on the drive system, impacting the vehicle's drawbar pull. Distribution of weight between the drive and the skis remain unknown, a parameter determined by the design of the chassis and sitting position of the individual user.

The prototype is placed in an uphill of angle α, enabling the calculations to cover the range of gradients a sit-ski possibly can encounter in use. However, a gradient of $\alpha = 10°$ is considered very steep in CCSS and $\alpha = 20°$ is steeper than what is likely to find in groomed ski trails.

With respect to wheel diameter, the two chassis designs are based on the same model. The realized physical prototypes with FBD and parameter names are shown in figure 6.7 and figure 6.9. The 2D FBDs are divided into two separate systems, the upper chassis ABC and the bottom frame, connected with the pivot of point A. The figures 6.8 and 6.10 show the FBDs without the background picture.

A method of theoretically calculating the magnitude of the normal force W_d on the drive wheel, is by the sum of moment around the pivot point A, assuming static conditions with constant velocity, $\frac{d}{dt}\overrightarrow{\mathrm{v}} = 0$.
One can analyze the system of the upper chassis ABC, assuming

$$\sum \overrightarrow{\mathrm{M}}_A = 0. \tag{6.1}$$

Keeping the values of F_t, $G_{seat,z}$ and $G_{seat,z}$ constant, the reaction force C_z can be calculated. C_z is equal to W_d and can be seen in figure 6.8 and figure 6.10. The weight of the system is separated into two different forces; G_{seat} and G_{rest}, where G_{seat} will be the weight of the user working on the seat. In the calculations, $G_{seat} = G \cdot f$, where

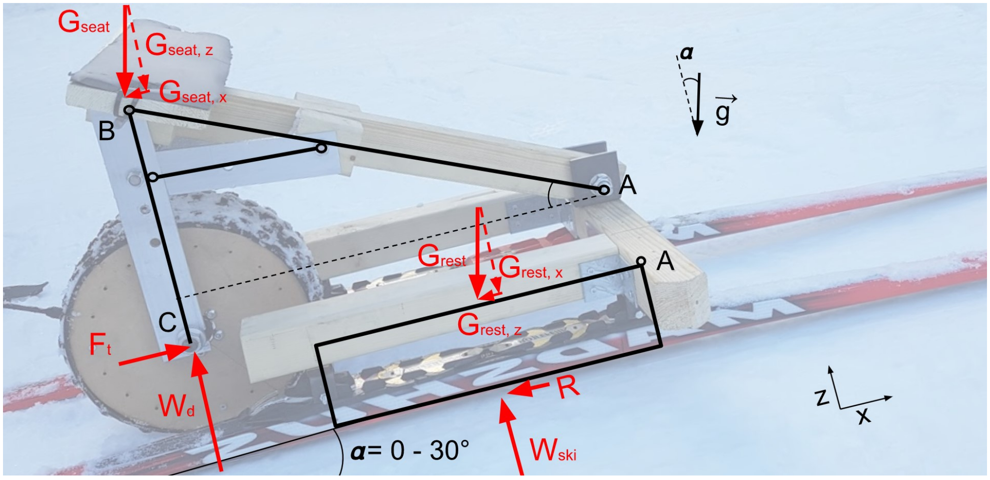


Figure 6.7: The forces acting on the chassis of the last prototype with a small wheel, in uphill of gradient α.

$G = m \cdot g$ is the total weight of the user + sit-ski, and f is the fraction of the weight working on the seat. G_{seat} is decomposed into the forces acting in the x-direction – the direction of velocity – and the perpendicular z-direction, as displayed in the FBD figures. The fraction f of the total weight which is distributed on the seat will be a variable changing from user to user and is dependant on the DP technique.

Displayed as F_t acting at point C in the FBD figures, is the reaction force from the snow working on the wheel shaft, being equivalent with the rimpull and tractive force F_t. The needed propulsive force to overcome the gravitation in uphill can be calculated from Newton's second law as in equation 5.1. Assuming no acceleration and R = 0, one can estimate the force as $F_t = mg \cdot \sin\alpha$.

Determining the lengths of the moment arms AB and AC from the pivot point in the x- and z-direction, W_d can be calculated from equation 6.1. These lengths rely on the chassis design and will hence be presented in the subsections below.

Inserting values for moment arms and forces in x- and z-direction into equation 6.1, one can estimate W_d with:

$$W_d = \frac{F_t\, AC_z + f \cdot mg(AB_x \cos\alpha + AB_z \sin\alpha)}{AC_x} \tag{6.2}$$

The necessary ratio between normal force and friction force can be calculated – which can be understood as the coefficient of traction from equation 4.7. Described in section 4.2.1, coefficient of traction is however calculated with the drawbar pull affected by wind drag, ski friction against the snow etc. Drawbar pull can be estimated with the tractive force F_t, assuming velocity is low and ski friction = 0.

$$\mu_t = \frac{F_t}{W_d}$$

In the calculations below, some variables are exemplified with constant values. The uphill is given a gradient $\alpha = 10°$, while the mass of user + system is set to $m = 95kg$. This results in a needed tractive force of $F_t = 162N$, the same value as in equation 5.2. The Matlab script used can be seen in Appendix C.

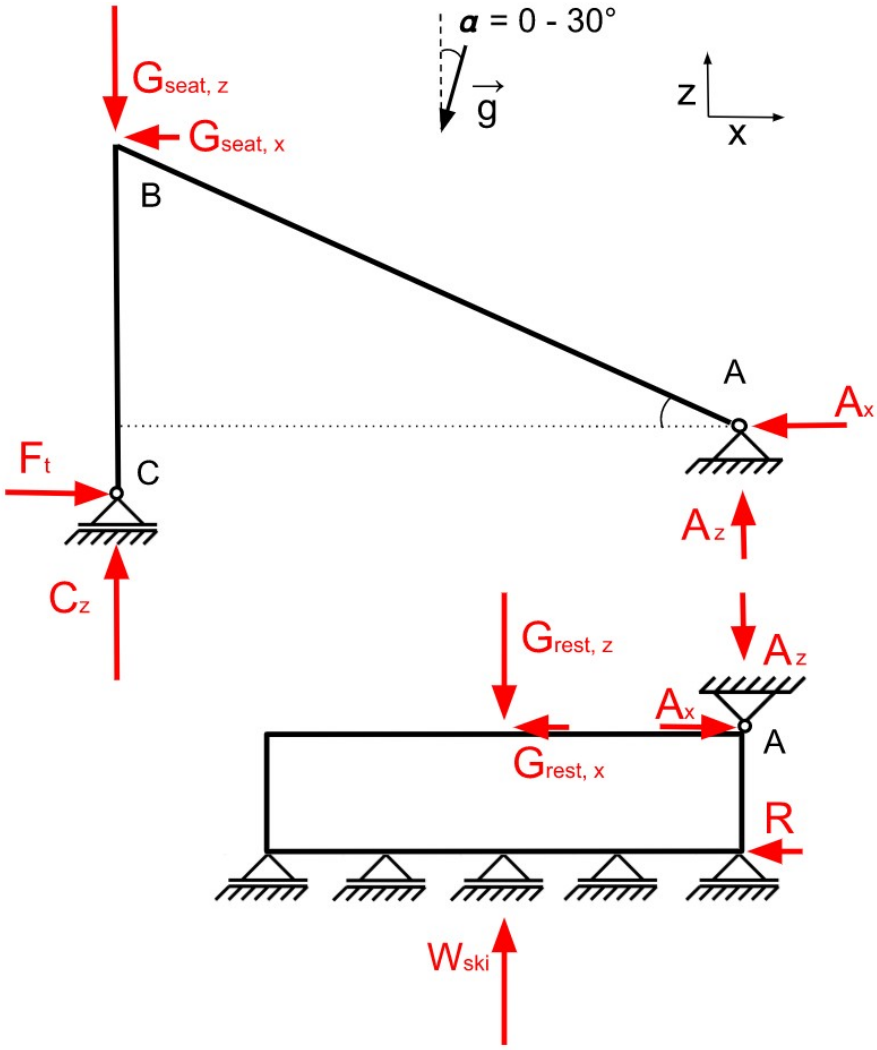


Figure 6.8: Free body diagram. The forces acting on the chassis of the last prototype with a small wheel. W_{ski} will be a reaction force.

Small Wheel

The suspension connecting the hub motor to the frame with two aluminum bars corresponds to the length BC in figure 6.7. Placed directly underneath the seat, the bars were connected to the shaft of the motor, keeping it in position and transferring most of the weight G_{seat} from the user into normal force W_d on the snow. As the hub motor is positioned below the pivot in the z-direction, the force F_t will contribute to an increased normal force on the wheel.

$AB_x = 0.40m$
$AB_z = 0.158m$
$AC_x = 0.40m$
$AC_z = 0.052m$

Inserting the values of the decomposed moment arms into equation 6.2, the normal force can be calculated. As displayed in figure 6.11, the normal force on the small drive wheel would be $W_d = 512N$, resulting in a coefficient of traction required to be bigger than $\mu_t = 0.32$. Concerning the chassis, these numbers should be sufficient to facilitate needed traction and drawbar pull, to assist the user DP.

26" Wheel

The suspension supporting the fatbike wheel was also fastened underneath the seat, but instead, the bars were placed horizontally since the wheel size did not allow a motor placement directly beneath the seat. The motor was positioned higher and further back compared to the prototype using a small wheel, so the drive force vector in the x-direction act above the pivot and will decrease the normal force W_d. How this influences the normal force on the drive wheel is indicated with the calculations and the plot in figure 6.11.

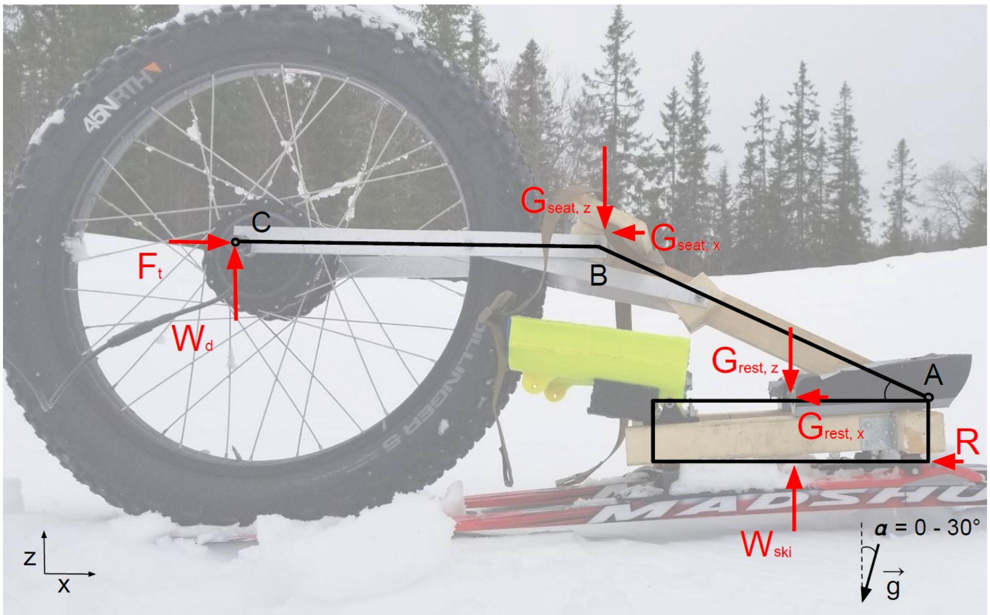


Figure 6.9: The forces acting on the chassis of the prototype with big wheel.

The distances from the pivot point to the forces in the x- and z-direction of the prototype with big wheel are given by:
$AB_x = 0.40m$
$AB_z = 0.158m$
$AC_x = 0.845m$
$AC_z = -0.093m$

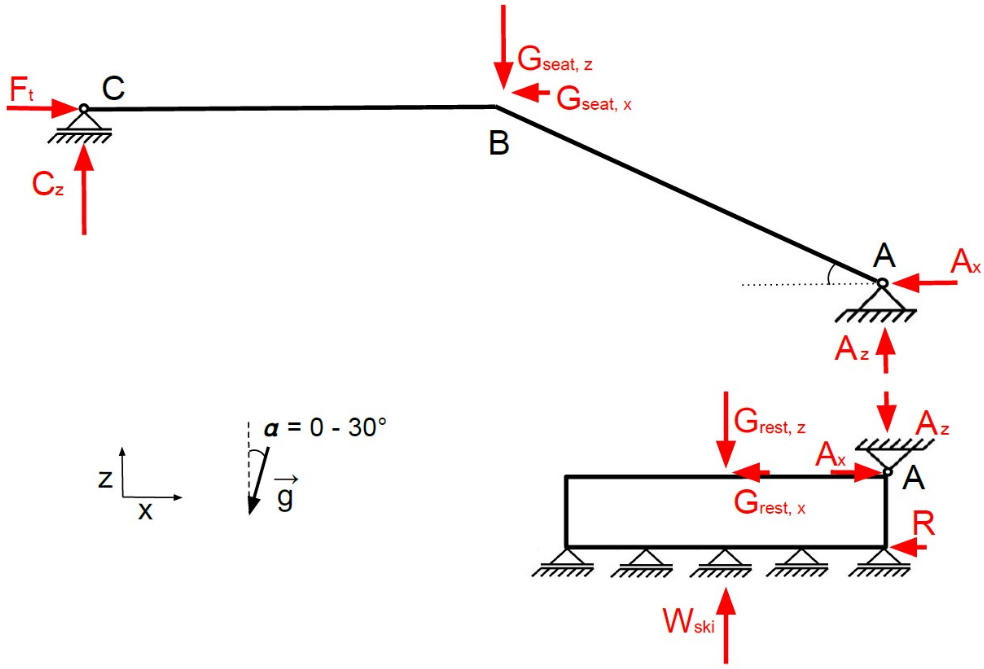


Figure 6.10: Free body diagram. The forces acting on the chassis of the prototype with big wheel. W_{ski} will be a reaction force.

The geometry lengths into equation 6.2 results in a normal force of $W_d = 215N$. The corresponding coefficient of traction will be required to be bigger than $\mu_t = 0.75$ to drive uphill of $\alpha = 10°$ – which might be too much for the drive system to accomplish. It is reasonable to say that having the wheel far behind the pivot will be leaving a small normal force on the drive wheel. Hence, this chassis solution is not facilitating good traction and drawbar pull. Nevertheless, these calculations should only be interpreted qualitatively, keeping in mind that the motor of the CCSS should be counted as assistance to the propulsion provided by the user DP.

Figure 6.11 shows the coefficient of traction vs. normal force for both prototypes, and is displayed as a function of the weight fraction f on the seat. The two graphs in the plot is presenting values of f from 0.35 to 0.65, and middle value of $f = 0.5$ is exemplified numerically. How much weight the user is placing onto the seat will have great significance to the normal force on the wheel, as indicated by the plot. Lower value of f will reduce the normal force W_d and hence require better grip and traction coefficient.

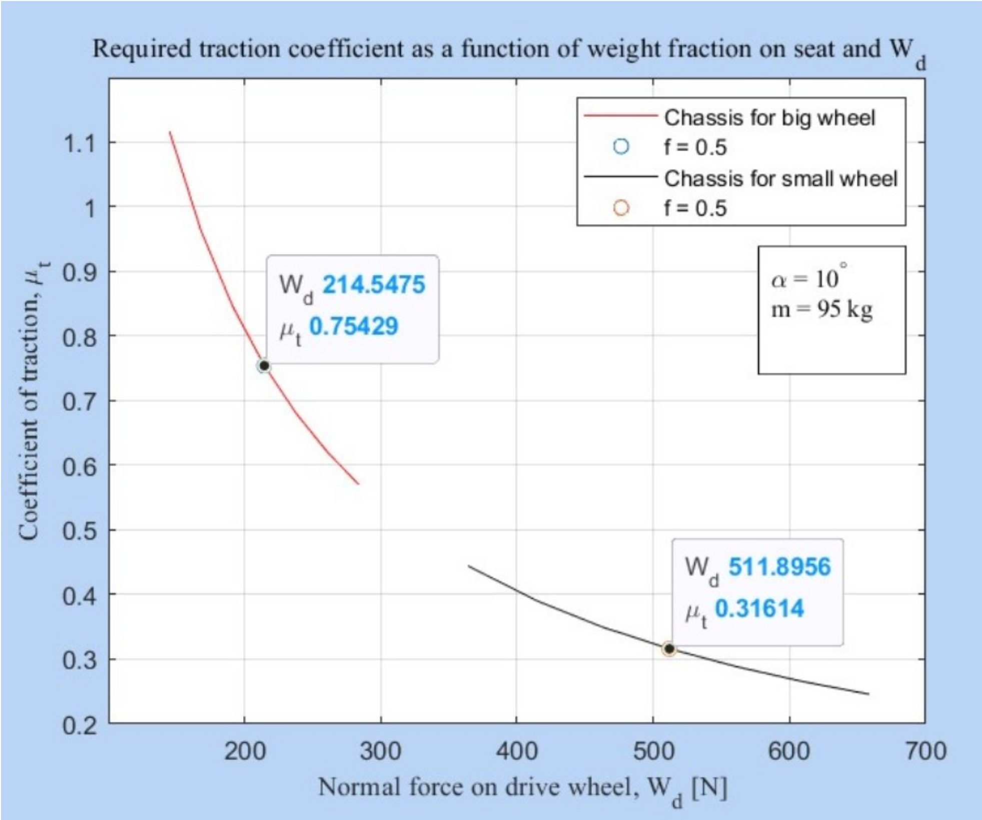


Figure 6.11: Plot to show influence of chassis geometry on normal force and coefficient of traction.

6.1.4 Testing

The pivot point chassis of the prototype was tested using the different drive systems; small wheel, large wheel and continuous rubber track. The tests are described in chronological order in Attachment A with objectives and results.

What can be understood as the filtered results of the investigation and tests are shown as bullet points in section 6.1.5. Since the testing was conducted first-hand, some of the presented results can be somewhat subjective as the experienced feeling of the use is included. Experiences from the tests are nonetheless valuable for further development. The stated aspects of the concept are general and intended to be as objective as possible without bias from prototyping.

The chassis design concept turned out to be valuable in the development process, as it was easy to build to assess the drive system. For able-bodied users with the opportunity to lean backward, the concept functioned as intended. In such a way, the pivot concept was successful, also facilitating low weight. However, the uncertainty is great regarding feedback from actual para users. The moving sitting position has not yet been tested with athletes, who might dislike the concept. External feedback is necessary to conclude on the chassis design with a pivot point.

6.1.5 Evaluation of a Chassis with Pivot in Front

	Advantages
+	Simple and cheap to build and prototype
+	Easy to apply force at the drive system intentionally
+	Relatively light weight
+	Minimal bending stress on chassis beams

	Disadvantages
÷	Not enough force at drive wheel if user is leaning forward (DP technique)
÷	Not comfortable with no means of shock absorber
÷	A moving sitting position will exclude the user group of competing athletes
÷	Probably not stable enough for users with high injury
÷	Novel concept not tested with users – much uncertainty

Table 6.1: Aspects of the concept with pivot point by knee joint.

6.2 Moving Sitting Position – Pivot Point in the Rear

Concepts with a moving sitting position were considered the less complex since they would not require springs or dampers to regulate the height of the drive system. An alternative placement of the pivot point was used in another concept using a movable sitting position. Instead of placing the pivot point in the front of the vehicle by the knee joints, the pivot point was placed by the ankles of the user giving the sit-ski slightly different properties.

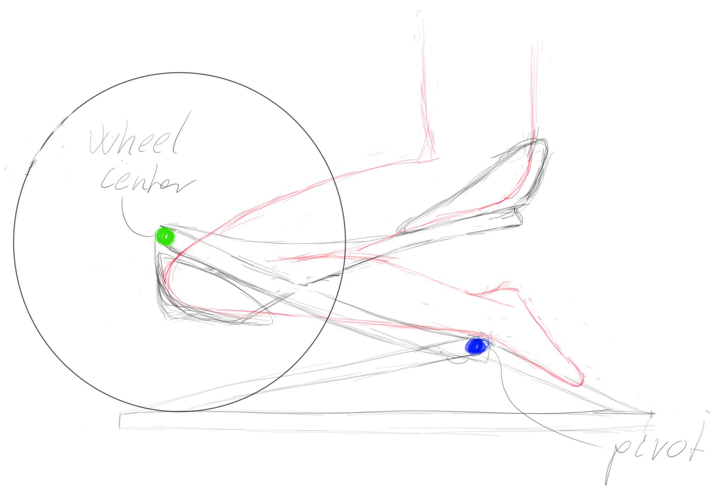


Figure 6.12: Side view sketch of chassis with a rear pivot point.

In the tests conducted using the prototype with the frontal pivot point, the behavior of the sit-ski was experienced to affect the double poling technique. The DP technique when using a knee-standing sit-ski will be most effective if the user leans forward with most of the weight on the knees as described in the pre-master in Appendix B, section 3.1.5. When the user leans forward some of the weight placed on the seat is lost. This causes the prototype with the frontal pivot point to lose traction as the normal force on the wheel decreases. Moving the pivot point to the rear was instead expected to transfer more weight onto the drive system and thereby providing better traction when leaning forward. The intention of this concept was, therefore, taking advantage of the movement, with a design that profits leaning forward.

The prioritizing of the drive system led to less investigation of different chassis concepts. The concept with a rear pivot point was therefore not physically realized by a prototype and has not been tested. A prototype of the concept was under planning using a similar approach as the frontal pivot point chassis but is only presented with sketches at this point.

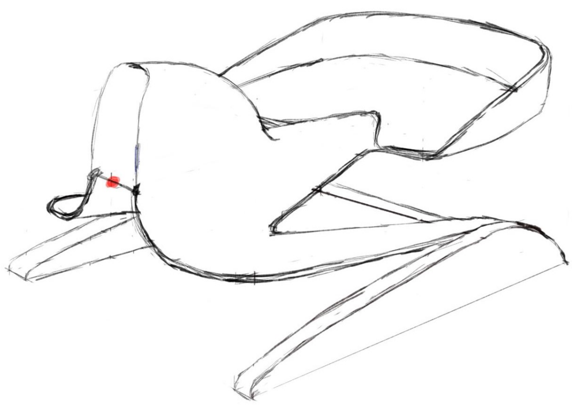


Figure 6.13: 3D sketch of chassis with a pivot point in the rear. The red dot indicates the placement of the wheel and the hood protects the skier from getting in contact with the wheel.

As the concept had not been investigated, the results found by testing the drive system was implemented in the sketch. The sketches of the planned prototype were therefore changed to utilize a drive system with a wheel size of 16". The prototype should also enable the use of a continuous rubber track as the choice of drive system was not decided. Sketches of a CCSS with a pivot in the rear and wheeled drive system can be seen in figure 6.12. and figure 6.13.

Some properties and behavior of the motorized sit-ski were expected to change by moving the position of the pivot. By introducing a pivot point at the ankles, the height of the knees changes with the snow as the knees are connected to the drive system. Having the knees connected to the drive system might complicate maneuvering of the sit-ski as steering is usually done by lifting the front of the sit-ski.

	Advantages
+	Enough force at drive wheel if user is leaning forward (DP technique)

	Disadvantages
÷	Difficulties maneuvering as the knees are not in a rigid position
÷	Novel concept not tested with users – much uncertainty
÷	User forced to have big gap between knees, due to the wheel location
÷	Difficult to adjust knee-height
÷	Difficult to include rubber track due to lack of space by the knees
±	Might be bouncy and uncomfortable with limited suspension
±	Easy to apply force at drive wheel intentionally (not tested)

Table 6.2: Concept of pivot point in the rear.

6.3 Rigid Seat Position – Leaf Spring

To include professional athletes, a fixed sitting position will be required. Some concepts with a fixed sitting position and a rigid chassis were therefore proposed. To facilitate the drive system sufficient normal pressure and some movement in the z-direction, the chassis would need to utilize a spring or damper.

During the ideation phase, the use of a leaf spring as suspension was suggested. The idea was that a leaf spring would provide enough pressure on the drive system and still be flexible enough to allow some movement. As the decision concerning the drive system had not yet been taken, two different suspensions containing leaf springs were designed to facilitate both a wheel and a continuous track. The sketches in figure 6.14 and figure 6.15 show the proposed designs.

To create space for the drive system – as of the design challenge described in section 4.6 – the concept utilizes the same open square bottom frame as the chassis with moving sitting position. The main difference from the other chassis presented is the additional support of the seat making the chassis rigid. A rigid chassis construction would be more robust with less movable parts. How the leaf spring suspension was intended to be fastened was different depending on the type of drive system.

With a drive system using a wheel, the leaf spring was intended fastened to the perpendicular front beam, positioned horizontally along the length of the sit-ski. The drive, in the form of a wheel, was to be placed at the end of the spring with some vertical movement allowed. The wheel size determines the length of the spring as the drive system was positioned underneath or directly behind the sit-ski. As the leaf spring works as the suspension it is important that the spring stiffness not exceeds the stiffness of the part surrounding the wheel – the wheel fork – causing bending in parts that should be stiff.

Using a leaf spring with a continuous track would require some features not needed for the wheel. To overcome obstacles such as loose ice and snow in the groomed track, the continuous track should be allowed some rotation. The small rotation was suggested solved in the design by attaching the leaf spring in a pivot underneath the seat. From the rotating attachment point the leaf spring was designed in the shape of a bow and

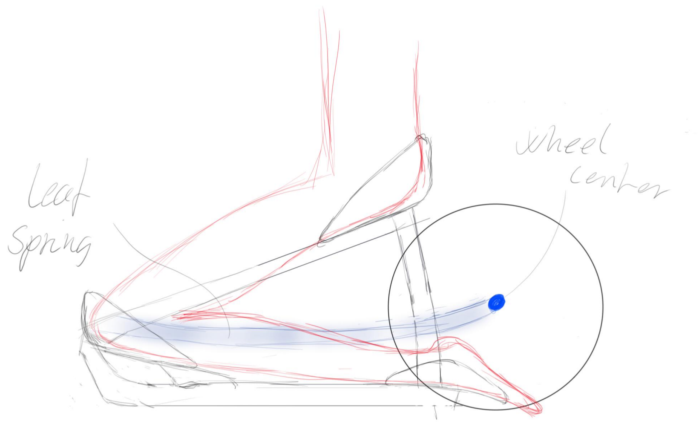


Figure 6.14: Side view sketch of rigid seat position with leaf spring connecting the drive system to the wheel.

connected to the front and rear shaft of the continuous track as seen in figure 6.15.

For the leaf spring designed for use with a wheel, the force is proportional to deflection experienced. The deflection of the leaf spring proposed used with a continuous track depends on the design and placement of the pivot where the weight of the user would work. If the spring is uniform, the deflection for this spring also be proportional to the force applied. The normal force can be estimated with $F = k \cdot u$ where u is the deflection in z-direction and k is the stiffness for the bar suspension and the bow suspension dependent on the material and dimensional parameters. Since the deflection would change with the track, in or out of the classic skiing track, the normal force would vary. The leaf spring suspension should provide enough force at the smallest deflection when skiing outside the groomed classic track, and still let the skis glide at maximum deflection inside the groomed track. The maximum height difference between the drive system and the base of the skis is 5 cm as can be seen in figure 4.2 in chapter 4.

The deflection of the leaf spring, and therefore the force applied to the drive, depends on the spring stiffness. The stiffness is influenced by the material properties and dimensions of the spring, including length. The spring should, therefore, be made with suitable stiffness by using favorable materials and designed properly. In other sports, composite springs are sometimes made of carbon fiber-reinforced polymer and such a solution could also be favorable in this project to keep the weight down.

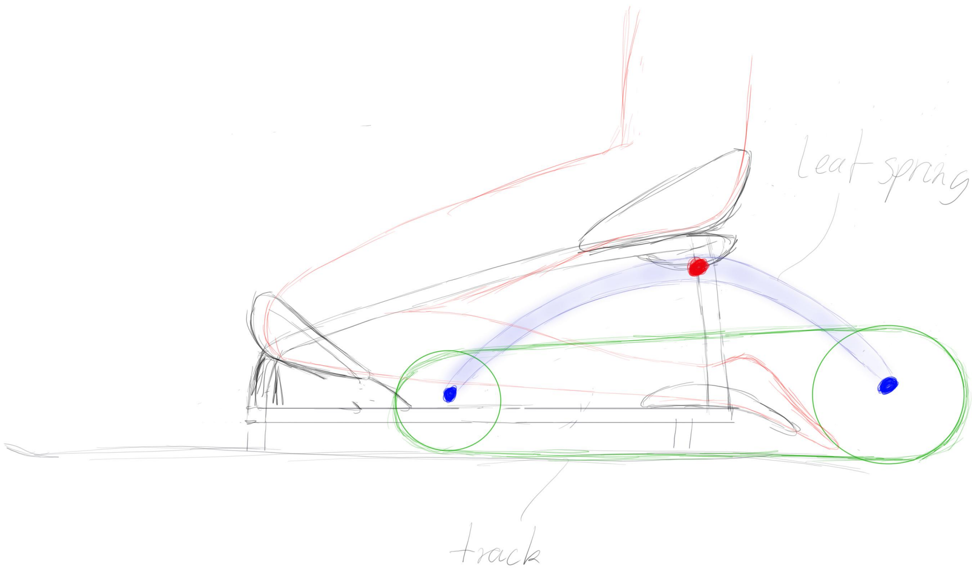


Figure 6.15: Side view sketch of rigid seat position with leaf spring connected to a continuous track.

	Advantages
+	A rigid sitting position will include the user group of competing athletes
+	Can be lightweight
+	Simple and few parts → reducing risk and wear
+	Easy to structurally maintain high normal force W_d (not intention only)

	Disadvantages
÷	Spring force reliable of ski track height; $\triangle F = k \cdot \triangle u$
÷	More normal force in the track than outside (opposite might be better)
÷	Requires knowledge of spring stiffness and normal force W_d at the drive wheel → relies on user weight, preferences and might require testing
÷	Might be difficult to customize stiffness of a spring if desired by user
±	Might bounce back – Eigenfrequency. Lack of damper? → solvable
±	Not interrupting the DP flow and technique (reasonable to assume, if fully developed)

Table 6.3: Concept of rigid frame with leaf spring.

6.4 Rigid Seat Position – MTB Inspired Rear Suspension

A suspension concept that could be combined with a rigid sitting position was inspired by the rear suspension of a Mountain Bike or MTB. With a similar solution as the rear suspension of a full-suspension mountain bike, the chassis could achieve the same beneficial properties if implemented properly. The concept utilizes the same principles used in bike suspensions where a shock absorber unit is applied to make the ride smoother.

The shock absorber was intended attached with pivots to connect the drive wheel to the chassis. The pivot points allow the wheel some vertical movement while the sitting remains fixed. An advantage of shock absorbers is the ability to customize allowed movement and rigidness.The gas pressure in shock absorbers can be adjusted to customize the normal force W_d on the drive wheel according to user preference and weight.

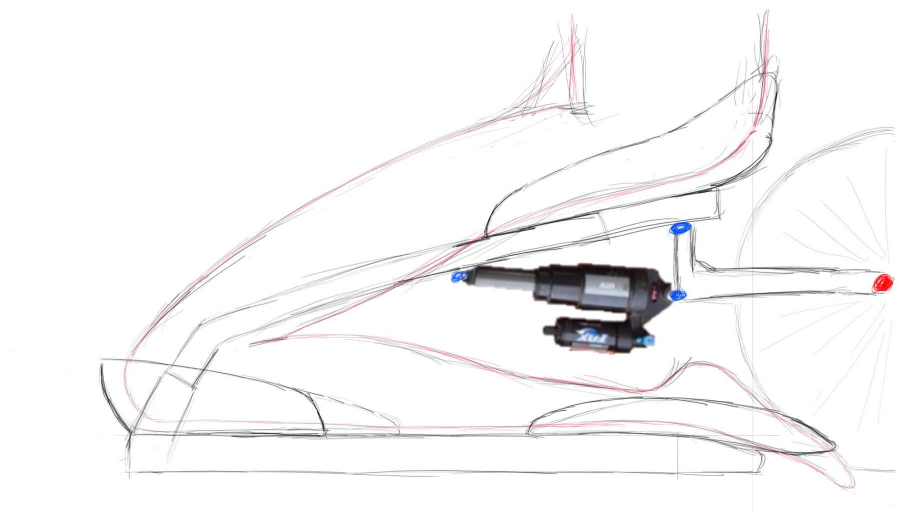


Figure 6.16: Side view sketch of a rigid seat position with MTB shock absorber. The support beams making the chassis rigid are not drawn to better show the shock absorber.

A benefit of implementing solutions from other product categories is that they are tested over a prolonged time and optimized for their field. With only a few adjustments, a well-functioning solution can be developed. The challenge of developing a novel product will be minimal as the proof of concept already exist in practice.

A solution with a dynamic shock absorber will be able to absorb the vibrations experienced in the ski trail making the activity comfortable to the user.

	Advantages
+	A rigid sitting position will include the user group of competing athletes
+	Probably comfortable solution regarding shock absorption
+	Not interrupting the DP flow and technique (reasonable to assume)
+	Commercial solutions of relevance exist → less development risk
+	Pressure of shock absorber can easily be adjusted manually
	Disadvantages
÷	Might be heavy
÷	Difficult to prototype with low fidelity and low budget

Table 6.4: Concept of a rigid frame with MTB rear suspension.

6.5 Outboard Drive System

The initial product idea was developing a complete motorized sit-ski where the motor was implemented in the design. A solution where an external drive system instead could be attached to the rear part of an existing commercial CCSS would also solve the project mission. As an analogy, such a motor can be seen as an outboard motor attached to a row-boat the outboard drive system was suggested mounted behind the seat.

Such a device would lead to a different challenge of applying force to the drive system and was not prioritized. But making it an external application would make the product available for more users, as of the design challenge described in section 4.9. It is therefore presented as a possible solution in the thesis.

	Advantages
+	Low price of end product – affordable for more users
+	Can be attached to the user's existing CCSS – no need to buy another personal CCSS due to the motor
+	Economical interesting concept for commercial CCSS producers and retailers
	Disadvantages
÷	Challenging to ensure sufficient normal force W_d
÷	The commercial CCSS might be customized to fit the drive system since the frame is not designed to withstand the applied stress of an attached propulsion system
±	Normal force W_d and weight of drive system will be behind the user

Table 6.5: Concept of outboard drive system attached to commercial CCSS.

Chapter 7

Design Function – Detail Design

This chapter will cover a variety of smaller functions that influence the choice of the design concept. The functions involve placements of external parts such as battery and motor controller, and some ergonomic challenges used to facilitate testing. The argumentation for the choice of propulsive force was also placed in this section.

7.1 Electric Motor

The CCSS was supposed to work by assisting the double poling user with propulsion. It was not meant to provide sufficient propulsion making the sit-ski self-propelled. A limited, but considerable motor power was therefore sufficient as described in section 4.1. The choice of assistive power was investigated and chosen early in the development process and the different means of providing force as well as the choice itself is presented below.

In the development work of the pre-master, rough ideas on how to provide additional propulsion were investigated. A mechanical solution utilizing the movements of the skier without any external additional force would be optimal to provide exercise. In the pre-master presented in Appendix B, a moving sitting position was explored and partly described in section 3.3. The goal was that such a forward or up and down motion could be utilized to assist propulsion of the sit-ski. To transform the momentum of the user into a useful force was found difficult. A part of the problem experienced was that such a movement impacted the double poling technique giving the skier less power with each double poling cycle.

Another mechanical solution was also proposed using a platform that turns sideways motion, shifting the weight from side to side, into forward motion. This sort of a penguin motion transforms the change of weight into motion similar to walking where the skis move parallel one at a time. The concept was not further investigated because the motion created was found to be small and would not contribute efficiently enough at the speeds expected. The side to side motion would also require supporting muscles that many in the user group do not have. Therefore, the solution was deemed not beneficial to continue exploring as it would require a lot of testing with the actual users.

Since the mechanical solutions were considered not beneficial to proceed with, a different concept was necessary. If a mechanical solution using the skier's motion to create force was impossible, an external power source needed to be implemented. To provide propulsion a motor was therefore considered. Of the different types of motors, an electric motor was preferred due to the higher torque to weight ratio. An electric motor would also have increased efficiency in the form of torque per watt of power input and reduced operational and mechanical noise.

From the theory presented in section 2.3.1, the motor holds torque also at low speed and when stationary. The area of the trail where assisted propulsion was need most was observed being climbs. The speed is the lowest during climbs and the contribution from the motor is most critical. It was also observed that during double poling of the steepest gradient the sit-skier might struggle and pause. When starting acceleration from zero at a gradient the need for assistance would also be high. On the other hand, at high speed, assistance from the motor is not needed. That correlates with the properties of an electric motor, making it a natural choice.

Comparing a BLDC motor to different engines in regards to torque, Diesel-cycle and Otto-cycle engines have their smallest torque on the lowest speeds, making them utilize less of their potential and not fitting the task. They are also heavy and make much noise, which is not considered to be beneficial in the ski trails.

The evolution and improved characteristics of the electric motor in the later years also contributes to a large market of small affordable motors that are easy to obtain at a low cost.

7.1.1 Wheel Hub Motor

There is a wide range of electrical motors in the market. An important task in the project was to find a suitable motor with enough power and torque. The dimensions of the motor should at the same time be appropriate and the motor should not be too heavy. This project will, therefore, focus on electrical motors made for electric bikes as these fulfill the required criteria.

The motors used in electric bicycles are usually placed in one of three places, the crank of the bicycle or the hub of either the front- or back wheel. The hub motors, front and back, are quite similar but the crank motor differs slightly from the others. Hub motors are placed in the hub of the wheel and drive the wheel directly while the crank motor is placed at the crank and drives the chain. There are usually also some differences are in regards to the input it takes to control the speed of the motor. Crank motors are often equipped with a device that measures the watt produced by the cyclist and use this to regulate the motor speed. Hub motors can have a similar function, but they could also be controlled with a hand throttle and be manually adjusted. It was a desire being able to control the motor manually and the choice of motor was therefore easy.

Usually, hub motors are either direct driven or geared. The two types have some different advantages. The direct drive motors are more efficient over longer distances and are faster. Direct driven motors are also able to do regenerative work, converting breaking into electricity to charge the battery. With the lack of gears, the motors are nearly silent. However, the direct driven motors have less torque and are larger and heavier which outweigh the other advantages. [42]

Geared motors make some noise, but are light and small. They are not as fast as direct driven motors, but still sufficient for the project. The geared hub motor also provides low-end torque beneficial when climbing. The torque, combined with the motor's durability, makes it a more ideal option.

The motors usually used in E-bikes are specified by measuring the instantaneous power output in Watts. Different manufacturers use different methods when calculating the watts and the power ratings are sometimes misleading. One of the reasons manufacturers use different standards are regulations of the power output in different countries.

Calculation of the wattage is usually done in one of two ways. The peak power of the motor is what the motor delivers with a fully charged battery and the maximum current flowing from the battery to the motor. Using the formula for input power presented in chapter 2, Mechatronics, and the efficiency of the motor the peak power can be calculated. The controller used determines the maximum current and for electrical bikes, it usually lies between 15-30 amps. The other way to rate the motor is using the continuous power. The continuous power is the power the motor safely can handle for an indefinite amount of time without overheating or getting damaged.

Figure 7.1: The electric motor used. [43]

The motors used in the project were delivered by Elsykkelbutikken. In addition to the motors, a battery, controller and some other equipment were also provided. The two motors were quite similar both being geared Bafang 36V 250W rear hub motors weighing 3.1 kg, making them a considerable part of the total weight of the sit-ski. The difference between them was the intended use. One on the motors was made to fit a regular bicycle tire with a normal rim. The other motor was made to fit a fat bike tire with a wider rim only resulting in some dimensional differences.

The motors were rated with 250W continuous power and a maximum torque given from the manufacturer of 45 Nm. The rotational speeds are specified as 310 for both the motors. These are assumed to be the unloaded maximum speed. A motor with the same specifics from the same manufacturer has been tested by a test site. The test gave slightly different numbers with the peak power tested to 438 W, a maximum RPM of 228 and a maximum torque of 33 Nm. [43]

A calculation with equation 2.2 presented in section 2.3.1 would give the peak output power, P_{peak} of the motor. With the specified voltage, the current of the battery and controller given 22 A, and a motor efficiency of 80% the equation gives a peak power of:

$$P_{peak} = V\ i_A\ E\ = 36V \cdot\ 22A \cdot\ 0.8\ = 633.6W$$

From equation 2.1 in chapter 2, the torque can be seen to be inversely proportional to the rpm. This means that maximum torque is achieved when the motor is stationary. However, calculating the maximum torque is not straight forward. Driving a motor at maximum torque for a long time will overheat the coils and cause motor failure. The torque in a BLDC motor is therefore usually limited at a nominal or rated torque, making the motor able to run with constant torque at most motor speeds and also when stationary. The rated torque corresponds to a rated motor speed and without information about the rated speed, it is difficult to obtain the rated torque. Only the maximum speed or the no-load speed that is given, using these numbers will give much lower value for torque. A representation of the rated torque and RPM is given in figure 7.2. [44]

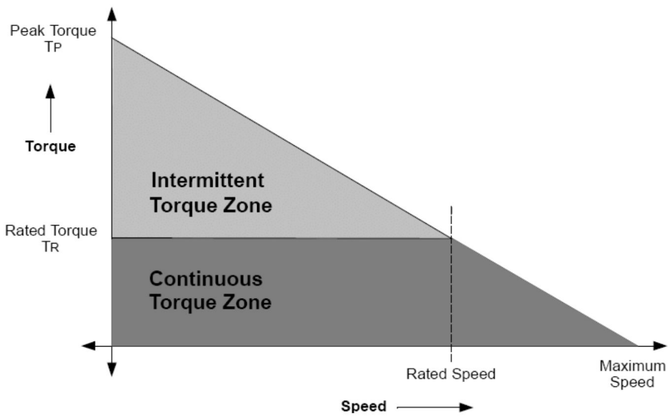


Figure 7.2: Torque speed relation. [44]

The motor usually works in the continuous torque zone, with only short bursts in the intermittent torque zone. Particularly, the torque can be above the rated torque when the motor starts from a standstill when extra torque is needed. If the motor runs at a higher speed than the rated speed, the torque decreases. As the given speed is considered to be maximum, using them to calculate the torque would give a smaller measurement than the given, but it was nonetheless worth investigating the given speed as the rated speed.

If the given rotational speed is the rated speed of the motor, the rated torque is calculated with equation 2.1 for continuous power and peak power respectively:

$T_{250W} = \frac{250W}{310rpm} = 7.7Nm$
$T_{633W} = \frac{633W}{310rpm} = 19.5Nm$

Both calculations indicate less torque and the given speed can almost without a doubt be said to be maximum speed. The rated torque is therefore not obtainable without doing physical measurements and the given torque were used in the further calculations.

If the motors are found to be too weak, more powerful motors exist that have higher torque and similar dimensions. Due to laws and regulations described below, these stronger motors were not applied at this stage. As a product similar to the one tried developed does not exist, an electrical bike was considered to be closest. The rules and regulations for electrical bicycles were therefore applied.

To get a picture of the torque needed to drive the weight of a person uphill, simple calculations have been made from equation 4.2. As described in section 4.2.1, the coefficient of traction μ_t and normal force W_d are required to be sufficiently big to utilize the torque, but regarding the choice of motor, these two parameters are not affected. From the calculations described in section 5.3.1, the theoretical torque needed to drive the user and CCSS uphill can be displayed with figure 7.3. Gradient and weight of the user will influence the required power from the motor, in addition to the radius of the drive wheel and loss in the system. Parameters affecting the needed motor torque will vary greatly. Hence, a set of relevant weights and gradients are displayed with the graph.

No examples of numerical values are displayed due to the limited relevance since the technical requirements are fuzzy and there is much uncertainty connected to the magnitude of the losses in the drive system for the prototype. No energy loss is assumed in the calculations to simplify the model. Figure 7.3 shows values for a drive wheel of an intermediate radius of 20 cm, corresponding to a diameter of 16".

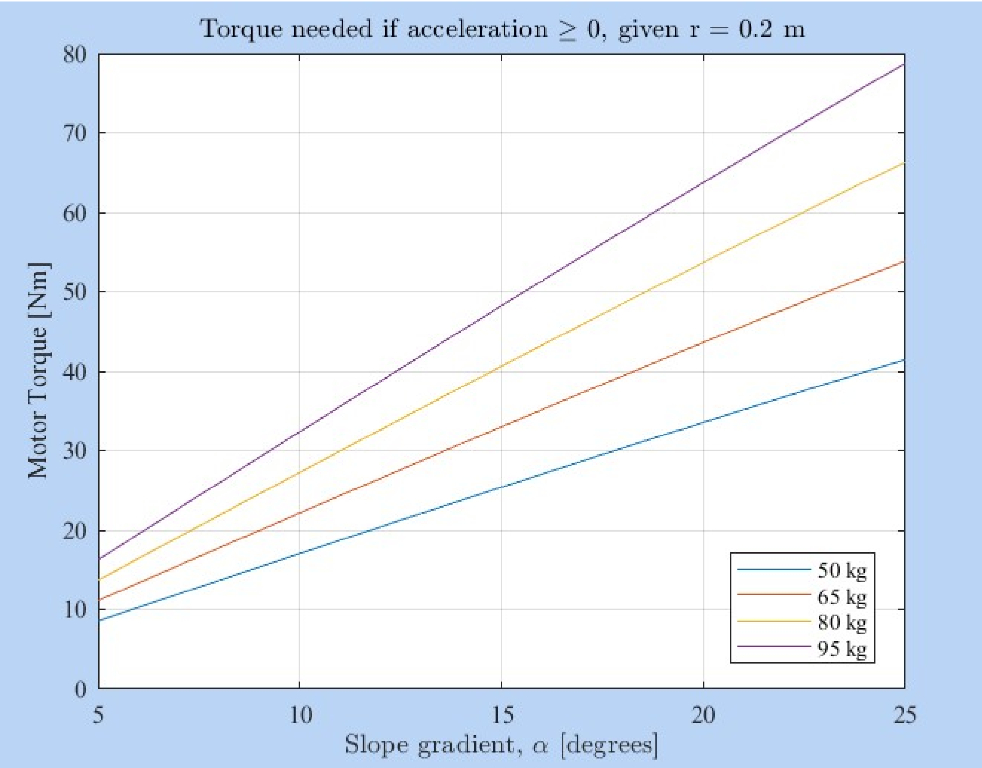


Figure 7.3: Graph of torque with respect to gradient and mass of system.

Rules and Regulations

Implementation of an electric motor to the sit-ski to aid propulsion means it would be classified as a vehicle and therefore regulated under the laws of small electric vehicles. In Norway, the use of equipment with motors or motor-assisted propulsion on the road or in nature is regulated by law. There are limits regarding both the power and speed of the vehicle while assisted by a motor.

The motor power used for assistive propulsion, as for electrical bikes, is limited to 250 Watt. The power limitation is based on the continuous power delivered by the motor. With the motor working assistive, the vehicles are allowed up to 25 km/h speed, above this speed the motor should not supply power. Self-propelled vehicles on the other hand, such as electric scooters, are quite new and not covered by the same laws. Instead, these vehicles only have speed limits. Electrical scooters and other self-propelled aids are limited to 20 km/h in populated areas such as a city or along a road. Outside these areas, where the motorized sit-ski is intended used, self-propelled vehicles are limited to 6 km/h. [45][46]

In competition, the use of an external motor is not allowed as described in the pre-master and can be found in the rules and regulations handbook of Para Nordic Skiing. [40]

Current Electric Hub Motor

	Advantages
+	Simple, standardized, cheap to build. Few parts (manufacturing cost saving)
+	Zero moving parts aside from bearings – less wear out
+	Reducing total weight by excluding mechanical transmission etc.
+	Increase weight of wheel (not a disadvantage since it increases normal force and traction on drive wheel)
+	Utilizing unused space inside wheel (hub) freeing up design space around frame
+	Runs quietly
+	No emissions

	Disadvantages
÷	If wheel of big diameter: High center of gravity
÷	Cold weather not favorable for batteries

Table 7.1: Aspects of the electric hub motor.

7.1.2 Additional Motor Equipment

The motor was delivered with some additional equipment. Of the additional equipment, a battery and a motor controller was included. Some information about these two parts follow in the next subsections.

Controller

A controller came ready-made and was used for the testing of the electric motor. The different inputs and outputs in the form of sensors, actuators and battery connected to the motor were also used at this stage. The inputs consisted of two breaks in the form of reversed push-button switches that cuts power to the motor when released, and a thumb throttle to regulate the speed of the motor. A control panel with an on/off switch was also delivered with the motor. The control panel showed the speed adjusted for a bicycle 26" bicycle tire and was therefore not applicable for all the drive systems. The motor was the only actuator connected to the controller. From the manufacturer, the controller ran on a current of 22 amperes. The battery provided electricity and was connected to the sensors and actuators via the controller.

(a)

(b)

Figure 7.4: Control unit and screen with on/off button.

Battery

The battery delivered with the motor was a Shanshan Hailong Battery case, containing 52 Samsung-29E 18650 rechargeable Lithium battery cells. It delivered 36V and 522 Wh with a nominal capacity of 14.5 Ah. In addition to the motor, the battery contributed to the increased weight of the sit-ski the most weighing above 3.4 kg.

Figure 7.5: The battery used in prototypes.

The dimensions of the battery also influence the placement of the battery. Finding a suitable position for the battery was sketched, wanting it to contribute to the normal force of the drive. The placement of the battery should also keep the center of gravity close to the ground to not influence the maneuverability of the sit-ski. The battery was possible to charge while attached to the frame, but it was nevertheless a wish to be able to remove it between sessions. With the use of a continuous track, a suggestion of placing the battery inside the track was proposed. This would not allow for easy removal. Other placements where suggested and can be seen in the morphological box in figure 5.1 or the sketches below.

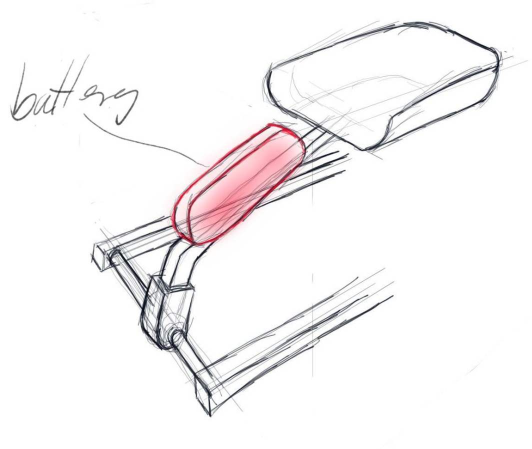


Figure 7.6: Battery placed on the center beam.

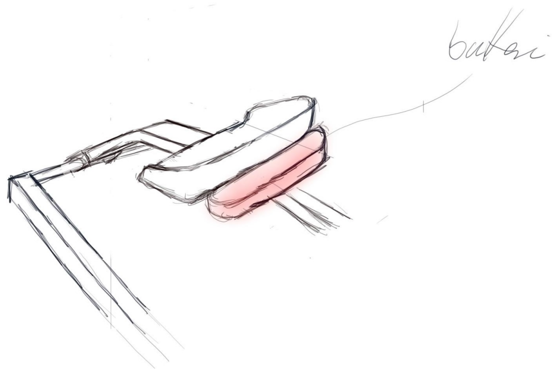


Figure 7.7: Battery placed behind the seat.

7.2 Motor Controlling

How the motor speed should be controlled while skiing is an essential challenge as mentioned in section 4.7. For a user to gain the full effect of the device while double poling the solution for motor control should not affect the technique. This means that the interaction between the user and the controller should easy and effective.

In existing solutions in similar products such as electric bikes, there are two main ways. The motor is either controlled automatically, measuring the power delivered form the user to adjust speed, or manually, controlled by the user him- or herself. The automatic control of the motor using the power provided fro the user as input is difficult to implement in the product developed as the power from the user is hard to measure. A new automatic solution would be constructed or the device would require manual control.

The manual control of the motor used by electrical bikes often consists of a gas pedal or throttle placed on the handlebar. This is possible while biking as the hands are holding on to the handlebar and can be used like the gearing system. As the propulsion of the sit-ski relies on double poling using the arms the solution can not be copied but instead be used as inspiration.

Figure 7.8: Example of a thumb throttle on a handlebar. [47]

Different solutions have been proposed and explored to solve the challenge. Since the propulsion is done by the user's arms, needing to use the arms to adjust the speed should be avoided as the sit-ski will lose a forward movement. Some of the solutions still rely on the arms to adjust the speed, in these solutions the placement and function are important factors. Some of the solutions are only presented while others were explored by themselves using simple mechatronic prototypes with an Arduino Uno and a smaller DC motor. The solutions were not implemented in the prototypes while testing.

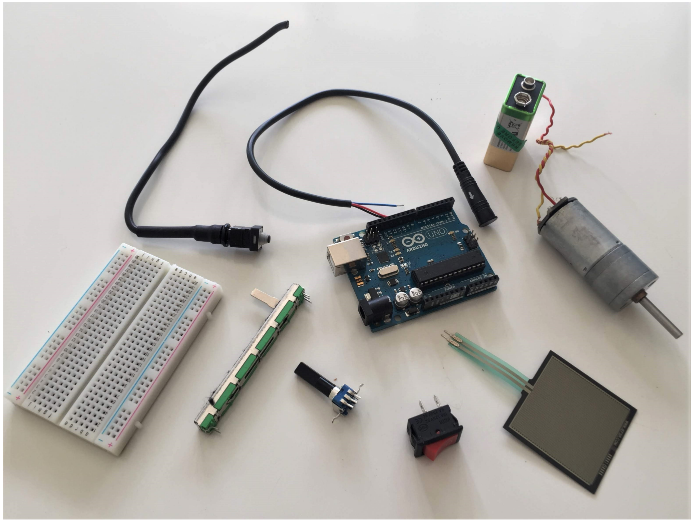


Figure 7.9: Equipment used for mechatronic prototyping

7.2.1 Motor Input and Speed

Before the actual control of speed, an upper limit should be set. Using the existing range of speed, the maximum RPM of the motor would result in a maximum speed of roughly 20 km/h. The expected speed of a sit-skier can be 10-20 km/h or above, and the speed of the motor might, therefore, require some limitation.

Constant Speed

The easiest concept proposed to regulate speed was by setting the speed constant. Setting the speed constant could be done using the existing software delivered with the motor and motor controller. If set constant, the speed must be set to an appropriate speed. Since the terrain changes, it might be beneficial having the opportunity to adjust the speed of the motor. There are also individual differences and differences in intensity of the explicit session. A constant speed is the easiest way to solve the problem, but it may not be the best.

Potentiometer and Thumb Throttle

The solution used during prototyping was the supplied thumb throttleThe thumb throttle was an analog rotary potentiometer containing a spring. Hence, a continuous push was needed to drive the motor. The need for a continuous push is not convenient as it occupies the hand leaving the skier left with one had to provide propulsion by poling. The thumb throttle is standard equipment to the e-bike motor but it is easier to operate on the handlebar of a bike.

Figure 7.10: Thumb throttle.

Improvements to this solution can easily be realized. The thumb throttle can instead be placed on the pole handle by changing the design to make it fit XC poles. While the throttle demands continuous pressure, removing the spring fixes this. The throttle could be adjusted and left still until the speed required adjustment again. Placing the throttle on the ski pole would make the interaction easier, but the user would still be required to adjust using their finger possibly losing their grip.

Figure 7.11: Thumb throttle with spring.

As the existing throttle is connected with a wire which limits the positioning. A solution used for braking on roller skis uses Bluetooth. This solution is possible to implement and will allow for different placements, like placing it on the ski pole. The design of the potentiometer with the Bluetooth might also be more favorable than the existing design.

Figure 7.12: Throttle on a ski pole. [48]

The use of a potentiometer to control the speed of the motor is not limited to the use of rotary potentiometers. A linear potentiometer without a spring was also suggested. A linear potentiometer would be easy to adjust and observe the throttle position. With a linear potentiometer, the placement would be important for the same reason as the rotary, but the options of placements are different.

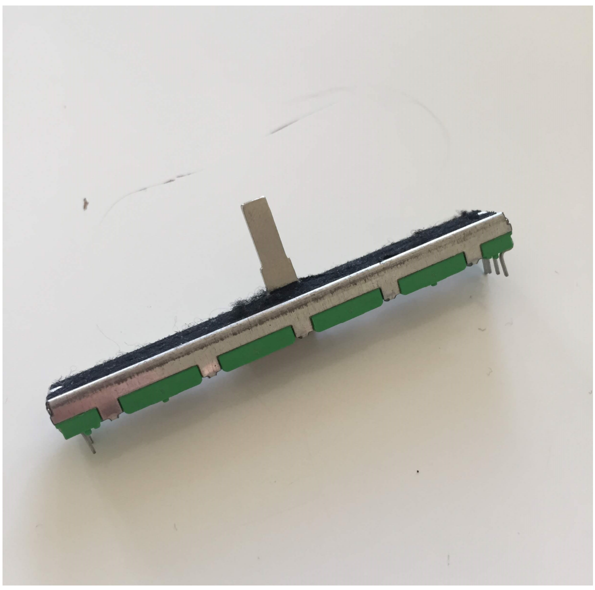


Figure 7.13: Linear potentiometer.

Several potentiometers were tested, both linear and rotary including the existing thumb throttle. As the potentiometers all gave the same output, 0-1023, it was expected that the control unit mapped the output into the right range, and switching the throttle would be easy.

Force Sensing Resistor

Since the user contributes to the propulsion with double poling, an automatic solution to motor control was desired. An automatic solution would require implementing a sensor that could detect changes in the movement of the user. It was suggested to utilize a force-sensing resistor to detect such movement.

An FSR was initially intended to control the motor and achieve an input that leading the motor to work in synchronization with the user's poling cycle. When working in synchronization the motor would aid in the same frequency as the poling motion. There was conducted a small test using a smaller DC motor and an Arduino to investigate if this was even possible with the use of an FSR. The test proved that such control is possible.

To investigate the feeling such a cyclic aid would give, another test was performed using the sit-ski prototype. During testing a helper used the existing throttle, pushing the pedal in the same cyclic frequency as the poling motion of the skier, alternating between maximum and minimum. The experience was not considered to aid the propulsion in a favorable way and the idea was discarded. Pushing the throttle creating an inverse cycle was also suggested ad tested, leading to a worse result. The alternating speed caused a disturbing motion for the user and made the usual poling motion more difficult. The test is described in the test logbook attachment in Appendix A

The idea of using the FSR in a future model was still not completely discarded as there are many sources of error in such an easy test. Through more testing and tuning with less difference in speed, such an alternating speed could be implemented and considered beneficial. But, at this stage in the development, it was deemed unnecessary to continue exploring.

The FSR could also be utilized differently. Through the law, the assisting electrical motor should only reach 6 km/h while the user is inactive outside populated areas and roads, as ski tracks are assumed to be. With an active user, the allowed speed is increased to 25 km/h as stated in the theory about the laws in Norway. To uphold this, a sensor could be used to detect motion or lack of motion of the user to adjust the speed of the motor.

A test to measure the change of pressure during the double poling cycle would need to be conducted if such a use of the FSR would be possible. Similarly, different positions of the FSR on the sit-ski should be tested to find the best placement. A similar easy test as the alternating speed was not conducted. But making the FSR control the motor by detecting changes in pressure would be plausible to show with such an easy test.

7.2.2 Safety Switch

For safety reasons, a stop function should be implemented. If the skier experiences an accident by either falling over, exit the ski track involuntarily, or losing connection with the throttle if the throttle was connected to the ski pole, the motor should stop. Using the

FSR as a motion detector described in the previous section solves this. But if such a use of the FSR is not possible, the stop function needs to be implemented differently.

In the existing equipment that was delivered with the motor two handlebar brakes were obtained. The brakes feature a reversed push-button that cuts power if the button is released. This button could be implemented if a fitting placement was found. A suggested placement would be in the seat. This may, however, stop the motor at not suitable times when motor power is needed. The positioning should, therefore, be investigated further.

Figure 7.14: Inverse push-button.

7.3 Bindings

Connecting a sit-ski to commercial skis can be solved differently. Though there are many existing solutions to attaching skis and the problem has been covered in a thesis from NTNU, the attachment of skis to the CCSS was solved simply and conveniently.

Most newer skis are equipped with NIS plates for easier mounting of bindings by sliding them on. Bindings are either made as two parts, a front piece and a back piece, or as one where the front and back piece are connected. Making a different connection to the sit-ski without the use of a NIS plate would require drilling into the ski. From the interview with a professional athlete, it was noted that the skis also were used by able-bodied for testing purposes. The switch between bindings used for sit-ski and regular bindings was tiresome and contributed to unnecessary use of time. The bindings were also a hassle to open and close when used with sit-ski.

Figure 7.15: The underside of the bottom frame with fastening mechanisms.

Instead of making an intricate solution causing much time and effort, two front parts of regular bindings were used per ski. This gave two connection points between the sit-ski and each ski and was deemed sufficient. One of the front bindings for each ski was slid on as usual with the possibility of slight adjustment. The other front binding was turned backward leaving the opener at the rear. With small adjustments, the center slot that guides the bindings when gliding on the NIS plate was widened. This enabled the binding to be slid on from the back part of the NIS plate. The back binding would work in the same way as a regular binding but be positioned in the opposite direction, seen in figure 7.16 where one binding is facing forward and the other backward. This made it easy to attach and detach the skis to the sit-ski. The bindings on the NIS plate are adjustable, making mounting of the sit-ski easier. The fastening mechanisms on the bottom frame were made the same in the front and the back, seen in figure 7.15.

Figure 7.16: The two bindings on the ski.

7.4 Ergonomic Parts

The development of ergonomic parts was not prioritized early in the development process. However, some parts were created to make testing more comfortable and less biased for external actual users. The parts were made to fit able-bodied test personnel. Using rapid prototyping in the form of 3D-printing, the parts took limited time and resources to realize. The quick CAD models made in SolidWorks of the knee support can be seen in figure 7.17. A 3D-printed seat prototype was also used.The seat had no back support but since it was only tested by able-bodied users, the lack of back support had no impact. Two 3D-printed foot supports were also used.

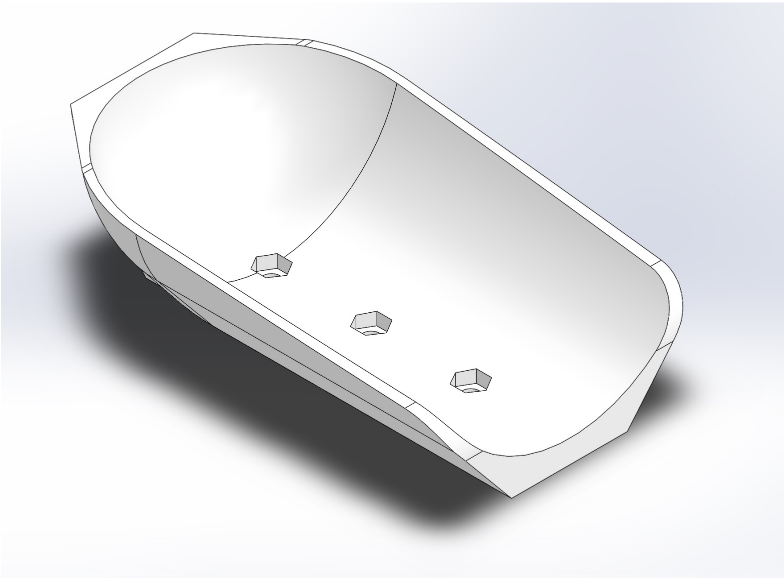


Figure 7.17: CAD of 3D-printed knee support.

Models to be used of actual users were started on as a part of preparation towards Ridderuka and the Para WC in Östersund. These models were slightly different. The seat model had a low back support. intended to be used with straps. The solutions should be possible to adjust, also for able-bodied users as the length of legs is different for individuals. To avoid pressure points on the legs and make the leg rests comfortable, foam was used as padding. Straps were used to fasten the user to the seat and improve maneuverability.

Chapter 8

Discussion

The development process involved different activities, the use of methods and principles that generated increased understanding and led to learning. The following chapter will use this increased knowledge to discuss different topics. Among the topics are how the user group and individual needs have affected the process. Specific for this project is the method applied; if it was suitable for the project, other possible approaches and if the method has been followed. Additionally, the evaluation of concepts, realized prototypes and testing methods will be discussed.

The high degree of uncertainty, unknown elements and unpredictable events that impacted the physical work with the evaluation of concepts led to an extensive discussion.

Development Method

The project covers the area of product development towards users with physical disabilities. In the introduction, some assumptions and statements were made to differentiate such a process from other development processes. The broad user group with individual needs and the need for customization was among the statements used to find a preferable development method.

Effects of Intended User Group

The empathizing revealed that products for users with individual needs required specialization, but the wide user group chosen caused the development to be generalized. The generalization meant disregarding some elements which could be challenging. It was not clear if the applied method with some generalization solved the great variation of the user group in a proficient way. The generalization contradicts the need for individualization of the product and could also lead the development process down the wrong path, ending up with a useless product.

A different way to solve this problem could be by looking at it from the opposite direction. Instead of looking to solve the problem for a wide user group, the process could have started with a smaller group. A smaller user group would impose some limitations, leaving the design space smaller and requiring more knowledge about the design challenges. This could have made the development process more effective as fewer solutions would need investigation. Adjustments and changes in the design could be implemented at a later stage after the product had been developed to accustom the product to a wider user group. However, this requires that changes to the product can be implemented in later stages or to the finished product. If not possible, the developed product will only be helpful for a small portion of the intended user group.

More specific for this project, the user group was not only diversified in terms of physical impairment but also in terms of ability and skill of the activity. The intended user group ranged from professional athletes to beginners. The goal was to accommodate more users to sit-skiing and contribute to increased satisfaction of skilled users by presenting new ideas of the equipment. Ranging in skill level, the requirements of the product should if possible cover both professionals and amateurs. However, the different needs for the user groups might be reflected in a final product so only parts of a beneficial solution can be implemented in products for each user group.

Applied Development Method

The question if a set-based approach was suitable for the process can be discussed. The development method applied was chosen based on the need for a flexible process to cope with the level of uncertainty and lack of knowledge about an ideal solution. The wide range of possible solutions and a wish to have a practical approach also influenced the choice of a set-based method similar to SBCE, where several solutions could be explored in parallel.

SBCE was used to investigate different solutions and functions at the same time to gain as much knowledge as possible. While the investigation of different concepts was made, the drive system became dominant influencing other functions more than previously believed. The development of the drive system consequently influenced the development of the other functions and demanded more resources. A set-based approach would possibly still be preferable as it enables testing of different functions even though the functions not were given the same amount of thought.

How the set-based method was applied also differs from the theory describing the method. To achieve a favorable result the method should be applied sufficiently. As explained in section 3.2, SBCE usually covers a wider part of the development process, including marketing and management. As it is applied the method used instead only covers the actual product development. It can be argued that this is only a small part of the entire process and the thesis a fraction of the project meant to be continued. The distribution of the available resources and limited time lead to discarding activities considered less necessary.

The prototypes evolved through an iterative process. The iterative cycles within the applied set-based method made it difficult to keep track of progress. Though some progress was possible to observe as the prototypes were developed, the outcome of learning with each iteration was harder to control. How much of the work contributed to the progression, aiding the development to converge towards one favorable solution, remains uncertain as the fuzzy process was challenging to manage.

At the phase the project reached in this thesis, only smaller achievement points were reached. More important milestones were close, with attending the event of Ridderuka, a functional prototype of one of the concepts was supposed to be finished with the possibility of end-user testing.

If a more linear method had been utilized, limitations could have been implemented at an earlier phase and the choice of concept could have been taken quicker. A linear approach could, therefore, have lead to a more productive development process without the need to investigate several solutions but rather focus on one. As there still are uncertainties to be solved, such a choice if taken too early could have lead to pursuing a solution that would not be favorable. A choice taken without enough information could have lead to late learning and the need for rework that would not be beneficial.

As the project was characterized by uncertainties and a large solution space, the applied method should contribute to learning and the investigation of different solutions. Subsequently narrowing the number of solutions to reach one optimal solution could be done when more knowledge was present. Other development projects could be solved using a similar method to achieve a favorable solution. From the thesis, it could be seen that the method helped to find and explore a set of solutions in different functions of the product. The drive system, however, was so important that the project could not answer if the applied concurrent development method used in this project would be beneficial for similar projects. At the same time, the utilization of an agile approach would probably be beneficial.

The project was imposed by few limitations, leaving many decisions to the developers. Having this many possibilities, the task may have been too wide and comprehensive from the start and could have been limited earlier, only to cover a smaller part of the project. The functions making up the product were however closely connected and testing possibilities of a single system would require a different approach. This could have lead to a more effective and fruit-bearing development process, but in that case, an investigation would have been necessary anyway to decide which system to prioritize. Much insight and many challenges were explored and the development of a novel product had progression, so the work was not without results.

Prototypes

The prototypes made during the work of the thesis contributed to learning and drove the process forward. Dividing the product into functions meant that the building of the prototypes was also divided. To begin with, the different functions were to be examined equally. As the drive system was found being most differentiating it also lead to it being the function in focus while prototyping.

Since the drive system was prioritized, other functions were investigated less, so the ambition of concluding with one complete solution needed changing. Being secondary to the drive system, the chassis was designed to enable testing of the drive solutions.

Only one of the concepts presented for the chassis design was made into a prototype. The concept with pivot was chosen as it was believed to be the easiest and safest allowing the drive system to be tested. The other concepts of the chassis contained more unknown factors and were therefore not build at this phase. To investigate further, some should, however, be made into prototypes and tested. While the chosen chassis concept worked, other concepts could have contributed in a better way. In later stages with a higher level of detail, other concepts were seen as equally solvable. An attempt was also made to start building the other prototypes but was shut down due to a lack of resources and closing of the workshop.

This early in the development the prototypes were characterized by low fidelity. The purpose of the prototypes was to show and test the function. The fidelity of the prototypes may, however, have influenced the results. With such rough models, it is important that the low fidelity not influence the function to be tested in such a degree that the test would become misleading.

The models most affected were considered to be the chassis and the continuous track. The drive system with a continuous track was heavily influenced by the low fidelity. It served as a proof of concept prototype and showed some useful results, but the low fidelity caused a somewhat unsatisfactory outcome. The model worked in a fashion that was considered insufficient for use regarding speed and added weight, but since the fidelity was so low, no conclusion was made. Since the model was tested in combination with the chassis model of relatively low fidelity, this could also have affected the results to some degree.

The chassis model used to assess the drive systems may have affected the results from the different systems. The behavior of the chassis used to transfer weight was fairly easy using a pivot point but the materials used and how the model was coupled lead to reduced stiffness of the structure. The reduced stiffness could have contributed to a loss of power.

A different effect of the low fidelity could be how it affected the user during tests. In the beginning, the prototypes lacked some features such as ergonomic structures. Without the ergonomic parts, the fit and comfort experienced was poor. Since the drive system was in focus, the comfort did probably not affect the results significantly.

Testing

Though the prototypes were made separately, testing was conducted by combining the functions of the prototypes. It was early considered the most effective way to conduct testing because of the dependencies of the functions, and it was not investigated if testing of separate functions was possible. Testing the separate functions one by one could, however, have given objective results, but probably demanding more resources in total.

Separated testing would have required an investigation on how the functions should have been tested to mimic the actual use. The combined testing may have required more work with assembly, but given that it resembled actual use more effectively it would give more reliable results. If possible to use both test concepts, the testing could both be effective and give reliable results.

The testing conducted throughout the thesis work was – because of safety reasons as well as how the resources were focused – conducted by able-bodied test personnel. The use of able-bodied testers meant that test results could be incompatible with results from actual users. By firsthand testing, the results can also be said to be biased and subjective, especially with the limited number of testers used. How the motorized sit-ski was to use might be subjective, but as the existing sit-skis also were experienced strenuous, the experience of help gained from the motor should provide some useful knowledge. The tests were used mainly to get the feeling of how well the motor was implemented and therefore the test person was not as important.

Even though intended users did not test the device, it was experienced that the motorized CCSS was exciting with several potential users expressing a will to try. By having a more direct discussion with potential users, input from tests could have been even more valuable and might have had a greater impact on the development process. However, testing with potential users would require the prototype to be adjusted to fit each tester. This early in the process, the generalization of the prototype led to testing with able-bodied was considered more effective and required fewer resources.

How the tests were conducted and their efficiency of exposing uncertainties leading the project forward, can be discussed. The amount of learning varied for each test and how well a test contributed to the path towards the primary goal was sometimes uncertain. That the test had a clear objective helped to evaluate the amount of learning, but some of the tests did not contribute as well as expected. The tests that did not contribute to the progression as expected, might have been insufficiently prepared and therefore not giving the expected amount of outcome. Some of the tests that did not provide pleasing outcome or reveal unknown factors of a concept, gave results in other areas that were not expected.

As the test conditions varied, avoiding the problem of tests being less useful, more standardized testing methods and test sites could have been used. More standardized tests would, however, be difficult to facilitate because of the shifting weather leading to different conditions. Testing should be easily available and it was considered important to test in actual ski trails as the device was meant to be used in such surroundings. There are indoor ski trails with similar conditions at all times, but not in the near proximity, so traveling to such a facility would require a lot of resources. It should also be mentioned that the device was intended to be used in many different conditions, and using standardized tests with steady-state snow conditions might lead to a deficient result. More standardized tests would possibly lead to more comparable results of the different concepts. With more comparable results, the choice of concept would be less complicated as the results possibly would be clearer. Instead of using more standardized tests, the last test in the test logbook in Appendix A shows a retest of one of the concepts was done at the same time as testing of a different concept. This was possible due to the set-based prototype of the chassis where concepts of the drive system were easily changed. Allowing the chassis prototype to work with several drive concepts helped to gain more comparable results.

Product

There already exist several solutions of CCSSs and therefore the work with the thesis began with a question if the market was fed and not needed another product. A small investigation was conducted where potential users were asked if such a product would be beneficial and be considered to fulfill an unmet need. The investigation revealed that a motorized sit-ski would contribute to new thinking in the market and was interesting to develop. Being only a limited investigation, it could be argued that a more thorough investigation should have been conducted, but the responses from the participants were so positive that such an investigation was discarded to free resources to the actual development.

As mentioned earlier in the discussion, as CCSS is an outdoor sport, conditions will vary. The testing of concepts showed that under certain conditions some of the concepts worked well and under other conditions, the performance was seen as not sufficient. It should, therefore, be discussed if the device should work on all conditions or if it is sufficient that it only works on certain conditions. Quite early in the process, this question came up, but it was quickly argued that the device should work in nearly all conditions. If the device only worked in some special condition, the mission of the project would not be solved since it would require perfect conditions to function.

If found through testing that different concepts are favorable for different conditions, would it be beneficial to have interchangeable drive systems, made for different conditions? So far in the project, there is no conclusion of drive concepts and difficult to say if different concepts would be favored on specific conditions. Using interchangeable drive systems, therefore, needs further investigation.

Another aspect of significance for the motorized CCSS is the type of sitting position. The choice of the sitting position made in this project can be seen as limiting the user group, as only a fraction of the users with impairments can use the knee-standing position. It is not certain that the chassis solution found will be possible to implement for other positions. Other sitting positions should be considered in further development.

Power Transmission System

Motor
The BLDC motor utilized was acquired through a firm, Elsykkelbutikken, selling electric bikes for the commercial market in Norway. As the allowed power for the motor used in electric bikes in Norway, the required motor was inside this limitation. Through the testing and calculations it was initially found to be strong enough for some of the concepts, but it could still be argued that a stronger motor could be beneficial for other concepts. Especially if the power transmitter is a continuous track, more motor power will be beneficial. It is not certain that a stronger motor would solve the challenges experienced with the concepts, but it might be worth exploring. A stronger motor would either way, since the dimensions and weight does not change, provide more power making the device more powerful.

For development, it would be possible to test a stronger motor, but it is not certain if the device would become illegal and therefore not possible to make as a commercial product. Since the product should be available for the commercial market, more investigation would be required about the law if the device would be equipped with a stronger motor.

Wheel with Tire vs. Rubber Track
The choice of type of drive system was not concluded in the thesis work as the evaluation of the concepts was not finished. The two main solutions, however, were narrowed down in terms of size and requirements of power and torque.

The concept utilizing a wheel was tested by a small wheel and a larger wheel, both coming short in some form. The small wheel worked well on certain conditions but struggled when the snow surface became loose. The larger fatbike wheel worked in looser conditions, but was experienced more unstable and struggled with low tractive force, due to the limited torque delivered by the motor and big radius. A solution with an intermediate sized wheel should, therefore, be investigated further.

The motion resistance provided by the drive system of the prototype with continuous track was too high, and the high resistance will be devastating for some users, probably many individuals among athletes if not lowered in a final product. The fidelity of the prototype had a clear influence on the resistance and should, therefore, be increased to investigate if the continuous track concept should be a part of the final product.

In comparison, a rubber track requires more power to run, either from the motor or the user if the motor is turned off, but have a larger contact surface contributing to better grip and traction. Both concepts need more investigation before a conclusion of a preferred system should be taken. If it is to be found that an intermediate sized wheel would have sufficient traction and power it would be preferred over the continuous track due to less complexity and weight, as well as possible standardization. The concept of a drive system with a rubber track might be unnecessarily heavy for the application in the ski trail, especially if the problem can be solved with a simpler solution as of a smaller fatbike wheel.

What is considered as a relevant sport to compare to, is conventional XC skiing. In the sport of skiing, minimization of motion resistance – in terms of friction between the skis and snow – is a key aspect to maximize speed and subjectively experience good flow. People from the competing XC skiing society know the importance of feeling good due to having what is experienced as good skis. The psychological effect of low motion resistance is not to be underestimated, especially considering the user group of experienced skiers. For instance, the positive effect of having exceptional glide of the skis might be greater than the effect of drugs. Hence, motion resistance is an important parameter to minimize regarding the motorized sit-ski, a statement that contradicts tracks in the decision of the type of propulsion system.

An aspect worth discussing is the destruction of the ski trail. The importance of this is relying on the opinion of the people using the trails, which will be a variety of individual and subjective meanings. It is reasonable to assume that a new type of vehicle destroying the ski trails will not be popular among skiers. Destruction of the groomed ski tracks should be minimized, but what would be the tolerated limit is unknown and depending on the location and type of skiers using the trail system. Ski trails are being used not only by XC skiers but also fatbike cyclists, dogs, walkers and skiers with pulks. This is tolerated to a subjective limit, not restricted by law, but the opinion of people. One can say that there is an ongoing dispute in the XC skiing society around people leaving deep footprints in the trails. In loose conditions with new snow, many skiers would say that people walking are not welcome. When the snow is older and the ski trail surface more solid, most types of users are welcome. If the motorized CCSS is to be realized as a commercial product, this debate will affect the success and should hence be taken into account regarding the choice of drive system. If not able to generate propulsion without destroying the ski trail at certain conditions, the drive system solution might not be acceptable.

Tire and Suspension
The type of suspension needed on the drive wheel will rely on the tire, or what is surrounding the drive wheel. A fatbike tire that is not fully inflated, will provide some shock absorption and suspending effect. Experienced in the testing of the prototype with a fatbike tire was a subjective feeling of comfort and pleasing shock absorption of the height variances from the ski trail.

Combining the two design functions, chassis with a pivot by the knees and a drive system with 26" fatbike tire, it was experienced appropriate suspension. On the other side, with the same category of chassis design – a pivot by the knees – but a drive wheel with rigid tire right under the seat, a lack of shock absorption was experienced.

A relevant type of sports equipment and product category to compare to are the different types of bicycles. The design relies on the intended terrain of usage. Road bikes are of less relevance to the motorized sit-ski, but various types of MTB might be a source of inspiration. Fully suspended bikes, with both front and rear suspension, is common. The disadvantage of additional weight due to the rear MTB suspension has been "covered over" by the implementation of electrical motors. Regarding suspension, it is of interest that fatbikes typically have no suspension, even though they are applicable in the terrain. This is a result of the suspension provided by the big fatbike tires.

Unsprung mass might be a bigger disadvantage for users with physical limitations than able-bodied people. Rigid constructions – if fully rigid implies that the entire device is unsprung mass – will result in the user absorbing shocks and variations in height. This is the state of conventional CCSS.

Customized Continuous Track
It is reasonable to assume that skins added on a belt had some potential as a concept, but compared to the prototype tested, it would require a much bigger contact surface – probably in the scale of a long track with running wheels. However, the test performed showed surprisingly bad qualities of the skins when experiencing slip. The state of the skin changed entirely, which was devastating for the functionality as it became useless for traction.

To investigate the concept further would require more resources and be demanding given the fidelity of the prototypes in the early phase of the development process. Customized rubber track with additionally attached traction material was never physically realized. However, communication with suppliers was started, but due to high prices and difficulties finding preferred sizes, no material was purchased.

An expected challenge was the snow and ice grains sticking in between the drive sprocket and track, creating additional tension that could result in the prototype dysfunction and potentially harm the user.

Traction
The traction was an extremely important quality of the motorized CCSS. With a coefficient of traction being too small, the concept would be meaningless. It was experienced that the tractive force from the drive systems varied greatly, depending on normal force on the drive wheel and the snow conditions, in addition to the tread pattern. However, it is important that it should work as an assistive device – not like a small snowmobile – considering Norwegian laws, so the product can be sold and used legally.

Chassis Design

Because of the importance of the drive system and its influence, the different chassis concepts were not investigated to the intended extent. With less investigation and evaluation, no concept was found to be favorable and more work is needed to find a favorable choice. Only one concept was built as it was considered the easiest and less complex. The remaining concepts have yet to be investigated by the means of prototyping and testing.

The choice of chassis concept utilized to investigate the drive system was taken as only small changes to a previous model was needed. The same concept was also continued to be used as it afterward was considered less complex to build and it enabled the implementation of the different drive systems.

The choice of only developing one concept was done to concentrate the resources towards the investigation of the drive system. If however the set-based approach was followed properly, the different concepts of the chassis should have been developed and investigated alongside one another. Investigating the solutions in parallel could have led to less investigation of the drive system, but at the same time, more knowledge towards the decision of the favorable chassis would be gained.

As all chassis concepts were not explored through the use of prototypes, advantages of the different concepts and comparing factors will be influenced by assumptions. It will not be discussed as too many assumptions will be made and a discussion based on uncertain statements not will contribute to a better evaluation of the concepts. The same can be said of the detail design which will need more investigation. Some discussion can be read where the concepts are presented in chapter 6 and 7.

Effects of COVID-19

The outbreak of COVID-19 led to different changes in the thesis in both development work and feedback.

The closing of the university also caused the workshop to close and working on the prototypes became impossible. Several prototypes were under construction and in a process of implementing changes solving challenges found from initial tests. The sudden stop in the development of new prototypes led to missing testing opportunities where the concepts should be evaluated. With less evaluation of the concepts, not enough information was gained to take the choice of concept to pursue in further work with the project. The project did not advance to the expected stage and the mission of the thesis was therefore not reached. With limited possibility of physical development, other work was conducted to give subsequent developers of this project a better understanding of the challenges the device is trying to solve.

Of the work that was interrupted and should be continued was increasing the fidelity of prototypes to get fewer sources of error and achieve improved test results in the form of learning. This was considered especially important for the continuous track in the drive system as internal friction influenced the existing model to such an extent that it was difficult to grasp if the concept would be beneficial or not. The internal friction led to an extensive power loss making it uncertain that the device would have enough power to aid the skier. With higher fidelity, less power was expected to be lost and testing would give more insight into the choice of drive system.

From testing of the wheel concept with two different sizes and the calculations, a more appropriate sized wheel was to be acquired and tested. Investigations led to finding a fatbike wheel size 16". Such a solution together with testing of the continuous track would narrow the design of the drive system and opening up to more testing of other functions.

Closing of the workshop led to a stop in prototype development and therefore new testing. The thesis was planned to take a practical and physical approach and base the evaluations on physical models and testing. Since testing of the concepts as prototypes were not possible, the evaluation of the concepts had to be conducted differently. With the main focus on the drive system and the challenge of providing traction and grip, this was tried solved by a more theoretical approach using calculations.

The calculations were based on the field of terramechanics, resulting in a need for self-education to gain an understanding of the field. The calculations were used to find comparable factors and variables to base the choice of drive system on. The simple calculations provided some additional insight, but not sufficient to decide a favorable drive system. The new field and the calculations, however, gave more knowledge about factors that influences the traction and explained what had been experienced during testing. The increased understanding of the variables influencing traction and grip are presented in chapter 4 and could help future work of the project by providing a foundation for evaluation.

Feedback

Testing by and feedback from the intended user group was considered important, but was not conducted at the earliest parts of the development process. After the initial phase, a new prototype meant to have higher fidelity was under construction to enable testing by people with impairments. The prototype was going to be an improved version of the first basic prototypes, not meant to be very close to a complete product, but with sufficient fidelity and safety features allowing tests by the member of the actual user group. Testing by and feedback from testers in the intended user group would be valuable for the continued development work.

Testing by actual para users was supposed to take place at two different events where the user group would be present. The first event where testing would be possible was Para WC in Östersund where extreme users in the form of professional athletes would be available for interviews and maybe testing. Feedback from extreme users would be very useful as they have a lot of experience with existing equipment and might provide feedback about function other users might not be aware of. Even though the prototype still would be of low fidelity compared to a finished product, early feedback would prevent rework if tests at a later stage had revealed problems with the design that could be found with early testing.

The second event that was meant to be attended was Ridderuka, a national event where para-users of different skill levels would participate. This event led to the opportunity of obtaining feedback from a wide variety of intended users with a wide range of experiences and skills. All this feedback would have great influence on future development and reveal if the total concept would be worth exploring further.

Both events were however canceled due to the shut-down and the feedback was not obtained. Instead of testing with actual para users with the new prototype, other solutions were considered to gain feedback. A questionnaire was considered used, but the idea was discarded as feedback based on pictures, videos and sketches could have given a false and overly positive or negative result. Compared to physical testing, feedback based on a questionnaire was not considered to contribute to the process.

Thesis Structure

For the thesis, the chapters of Introduction and Discussion correspond to the IMRaD model, but not the main chapters of Method and Results. It is reasonable to say that the method and results are fuzzier in a product development process, compared to what the IMRaD model is optimal for.

The main chapters of the thesis include the chapters from chapter number 3 to 7. Chapter 3, Method – The Development Process, is working like a Method chapter. It describes the methods used based on the theories and as to show how principles from different methodologies can be applied in a development process. The actual work conducted is not presented in this chapter, the practical work and what has been executed in the project is described further in the respective concept chapters 5, 6 and 7.

Chapter 4 works as a basis for the development work because it describes the challenges faced during the development process that was tried being solved. The chapter is considered important since it describes the challenges faced during the development process and what is required of a good product.

What corresponds to the result chapter of the IMRaD model, are the chapters 5, 6 and 7, presenting the concept solutions of the design functions. Chapters 5 and 6 present different concepts in each section, sets of solutions to the respective function of the chapter. The intended results of the thesis were evaluations of the concepts through prototyping and testing. Because of the limited building and testing, the chapters only present a partial result and there is still much work to be done to converge towards one preferred solution based on the concepts. Chapter 4, describing the basis for development, should, therefore, be counted as preliminary results as it provides the foundation for development of the motorized sit-ski. For subsequent developers, chapter 4 might be of value and is advised to read because of the limited evaluation of the remaining concepts.

Chapter 9

Conclusion and Future Work

Development of assistive equipment to aid the users of CCSSs has been the foundation of the project, as well as mapping the challenges to be overcome. The concept of a motorized cross-country sit-ski, realized with prototypes, proved to be useful and showed potential, so further development can be fruit-bearing. The prototypes enabled testing and showed dimensions, but due to the low fidelity, some of the results were considered inconclusive needing more investigation. More insight towards a decision of an optimal solution would have been desired. The project was still characterized by uncertainties, so the choice of concept was postponed. Much development work remains and commercialization is not yet thought of.

In icy conditions with old and relatively solid snow, a small wheel with low contact area and not beneficial tire tread pattern provided sufficient traction. The same drive system was however useless in more common snow conditions with new and looser snow. Realized was also a prototype with a drive system based on a 26" fatbike wheel which proved to facilitate minimum destruction of the ski trail, but limited drive force. Concluded regarding the drive wheel was that the diameter should be reduced compared to the 26", while the fatbike tire is recommended to be implemented further with the advantages of low rolling resistance of wheel, being commercialized and fully developed.

A continuous rubber track was developed and tested in another prototype. Testing showed that the rubber track provided significant traction, but also reducing the transmitted power due to the low efficiency of the track system. The low fidelity of the prototype influenced the test, so a new upgraded version was about to be finalized when the outbreak of COVID-19 interrupted the process as the workshop was closed. A drive system solution with continuous track might be unnecessary heavy for the application of assisted propulsion in the ski trail.

The chassis of the motorized sit-ski was considered a secondary function, not being prioritized before the drive system solutions converged into one concept. Used in the prototypes was a chassis with a moving sitting position, with a pivot point by the knees. For able-bodied users being satisfied with leaning backward while skiing, the concept of the chassis functioned as intended and successfully facilitated the assessment of the drive system. However, while leaning forward the normal force on the drive wheel was too low, resulting in slip and minimum assistance with propulsion. It is believed that a motorized CCSS to be used by competing athletes must consist of a rigid seat position.

Design challenges that proved to be difficult to solve, include destruction of the ski trail in loose snow conditions. The varying snow conditions can be challenging. Also providing the same normal force when the drive wheel was working higher or on the same level as the skis, has been challenging. To produce a motorized sit-ski being lightweight to facilitate maneuverability and maintain the subjective feeling of sports equipment being fast, is expected to be demanding.

Testing with actual para users was not conducted in the thesis work. Events planned to be attended were canceled. These tests would have given essential feedback from end-users needed to objectively evaluate the prototype and concept. Regarding the further development of the concept, it is advised that testing with intended users should be prioritized and conducted at the earliest time possible.

The next step in the development process could be a decision on the type of drive system. Testing between two prototypes of higher fidelity with rubber track vs. wheel of intermediate diameter with a fatbike tire is recommended. Then, the development of expedient chassis, motor controlling and detail design follow. To be pointed out, is that testing of the motorized CCSS in a ski trail with actual users with physical limitations should be prioritized at the earliest time possible.

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Appendix A

Test Logbook

The test logbook from the thesis work is attached – an appendix of 11 pages describing each test in detail with a few pictures showing the prototype and snow track. Appendix A is to work as a report describing all tests in chronological order.

Two test locations were used, due to the purpose of standardization. Both were outdoors, affected by the rapidly changing weather in Trondheim. The location noted as Skistua was the ski trail placed between Skistua and Gråkallen in Upper Bymarka in Trondheim. The trail was relatively flat, with a few small hills and turns making a loop. The snow conditions there were often colder and dryer than the other test location, Ferista. The ski trails next to the parking lot at Ferista in the lower part of Bymarka were hillier and at a lower altitude resulting in other test conditions. One bonus test location was the snow-covered ground outside of the workshop, used due to very short travel distance and the convenience by testing critical functions of new prototypes before traveling to the field.

The testing was conducted by the same three students that developed the motorized sit-ski. Two of them had a background as cross-country skiers with experience from ski testing at a national competition level and had tried to empathize with the users and activity of CCSS, as described in the pre-master, but were able-bodied. The test conditions varied greatly due to the change in snow conditions and the temperature was the only measurement made. Hence, the results are subjective, but efforts were made to avoid biased statements.

In general, to learn and get usable feedback on the concepts to drive the product development process further was the purpose of the testing.

Pictures from the tests showcasing ski tracks and footprint from the sit-ski were edited by increasing the parameter of contrast to highlight the variety in impression on the snow from the vehicle with different drive solutions in different snow conditions. Photography is a convenient means of monitoring the complex state of the snow and the mark left by the drive system, and helpful for the designers to evaluate and compare solutions after testing. The track mark left in the snow can among other parameters reveal approximately degree of slip and penetration depth, that depend on the snow condition, normal pressure from the weight of the user and equipment, shear stress applied to the snow from the drive, and tread pattern on tire or tracks.

The date of each test day is listed as headlines, given with Appendix page number below.

Contents

02.12.2019

- Place: Skistua.
- Conditions: New snow.
- Prototype description: Two commercial CCSSs and The turning prototype
- Test objective: Obtain a feeling of how commercial sit-skis are in action, how they interact with the snow and how they compare to the turning prototype in testing…
- Result: Heavy weight of the rigid, commercial CCSS. The turning prototype followed the track much better through turns but was also harder to trust and steer outside the track. A lack of stiffness in the frame was experienced, but whether it was positive or negative remained to be agreed on. The activity of CCSS was experienced to be exhausting (needing assistance with propulsion.)

10.02.2020

- Place: Outside of the Workshop, Gløshaugen.
- Conditions: Grass covered with a few centimeters of loose snow (both old grains and new snow).
- Prototype description: Small wheel with studded tires, dimensions: D=21cm, Width of MDF=3cm, and studs w=4,5cm. The sit-ski was an old prototype used to test turning with two pair of skis.
- Test objective:
  - To rapidly test if the prototype functioned as intended or reveal any surprising failures before going to the ski trail.
  - The Drive: Proof of concept – if the motor was fitted for the task, had enough torque etc.
- Result: High degree of slip was experienced, so wheelspin resulted in digging through the snow down to the grass, and the drive wheel suspension rotating around pivot point reached its lower position, so minimal force remained on the drive. The wheel needed more traction and more normal force. Motor probably strong enough. Fidelity of prototype was very low with improvement on pivot point needed.

Figure 1: Pre-test of a small wheel.

12.02.2020

Test 1

- Place: Ferista.
- Conditions: -2 degrees. Both relatively solid snow and coarse grains not sticking together (like sugar) where it was recently groomed.
- Prototype description: Same old turning prototype customized for assessing drive wheel in action. The motor placed far behind, as seen in picture. Pivot point stabilized.
- Test objective:
    - The Drive: If motor was strong enough (self-propelled in uphill), grip with studs, magnitude of weight on the drive, Motor force sufficient? Destruction of ski tracks?
    - The Sit-Ski: effect of leaning backwards or forwards on the tractive force. Pivot point as concept. How stable this low-fidelity model was.
- Result: Acceptable grip. Drive force sufficient (or at least for able-bodied user). The motor was fitted for the task. For the heaviest test person more weight was needed on the drive system to avoid spin. The print was considered acceptable, but in the section of the trail that was recently groomed, the middle of the track was a bit destroyed. The amount of spin was very reliable of the snow conditions – and this day the conditions was “fast”. The motion resistance was low from the wheel and hub motor.

Figure 2: First test of small wheel and mark left in the ski track.

One can see from the right picture in *Figure 2* that the rut from the wheel was not deep and not implying slip, but was placed in the left side of the groomed track at solid snow conditions.

Test 2

- Place: Ferista.
- Conditions: Same as Test 1, coarse grained cold snow.
- Prototype description: Attempt to isolate the parameter of normal force on the wheel. With a pivot point over the rear ski, the weight of a standing person was placed a distance x away from the pivot point, to be able to vary the pressure on the drive wheel. $\sum M_o = 0 = N*L - W*x$.
- Test objective:
    - The Drive: Assess the effect of normal force on the drive, how much needed to get grip or spin, and effect of distance from the applied force.

- Result: The more weight closer to the drive wheel, the more traction, at least for the heaviest test person of 90 kg. For the medio weight test person, about 2/3 was sufficient at the flats.

Figure 3: Test setup based on previous Turning prototype.

Figure 4: Testing of varying normal force on the drive wheel.

Test 3

- Place: Ferista.
- Conditions: Same as test 1, coarse grained cold snow.
- Prototype description: Concept of skins (friction material with hair used in backcountry skiing)… Skimo skins attached to the small solid wheel of MDF, w = 3cm. Same sit-ski chssis as Test 1.
- Test objective:
    - The Drive: If skins had the potential of being the surface material of the drive system (next step tracks?)
- Result: Devastating. Tractive force not even close. The skins did not have enough traction, resulting in full slip, wheelspin, so the skins eventually got destroyed because the hairs changed direction, pointing straight up. Useless on wheels. Not impossible to make work on tracks with big contact surface, but the concept will not be prioritized for now.

Figure 5: The state of the skins before and after testing.

19.02.2020

Test 1

- Place: Ferista.
- Conditions: Air temp: +3. Solid, old snow, frozen after last grooming. Big snow grains.
- Prototype description: New low-fidelity prototype. Bottom part of the frame like an open square, with space for the drive to work between the feet like in the rear. Stiffer chassis design with pivot point in the same position in front, but drive wheel right under the seat. Wider wheel, w = 9cm, but same radius. Long parallel traditional skis (Madshus skate).
- Test objective:
    - The Drive: Does the wheel function as a concept? What needs to be improved? More stable now? Footprint?
    - The Sit-Ski: Sitting height? How does it feel? Effect of motor position.
    - Motor controlling: Test of external controlling of thumb throttle, varying power.
- Result: Very good response outside the ski track was experienced, driving up steep climbs without double-poling. Worse in the track, with some degree of slip. Accelerated surprisingly good, considering the motor was the same.
  Great conditions for this concept, noting that these conditions were also beneficial regarding propulsion, so the concept of motor propulsion was less needed. A few places the snow did not stick together as good, resulting in some degree of spin.
  The diagonal beam between the thighs was still a bit wobbly (due to the pivot point), but tolerable. Humps were experienced directly with the wheel right under the seat. The wheel might jump after humps, inducing a moment with lack of normal force and lack of traction. (This could be solved, for instance with a torsional spring by the pivot point).
  A feeling of how it is to DP using both arms with propulsion assistance from the CCSS was obtained – quite different than with one arm. The total propulsion was great and high speed was easily achieved. Fun to experience such a good flow without getting exhausted. The varying power from the motor did not feel very disturbing, but could appear surprisingly, which was a highly

subjective opinion. Critical for the chassis design regarding pivot point in front, is that one leans forward in the uphill to activate more abs, which results in less normal force on the drive and a lack of traction.

Figure 6: The mark outside the ski track from the ski and the studded tire, implying no slip and low indentation depth.

Figure 7: The ski track before and after the device drove over.

The two correlating pictures in *Figure 7* indicate how much the middle of the track was destroyed and changed character. Worth to notice is that the middle of the track was weak at this point, but it is reasonable to assume that this is beyond what some local ski tourists can tolerate of impact on the common ski track from the drive wheel.

Test 2

- Place: Skistua.
- Conditions: 0 degrees C. in the air, but colder in the snow. Freshly groomed, new snow. Looser conditions. Sunny.
- Prototype description: Same as Test 1 this day.
- Test objective:
    - The Drive: Effect of softer snow conditions.
- Result: Too bad traction. High degree of slip. Neglectable tractive force, which is devastating for this concept of a small solid wheel with this tire tread on lose snow. Improvements necessary, as these conditions are typical and important to handle for a motorized sit-ski. The destruction of the ski tracks was extensive. Better result without applied weight on the sit-ski.
  Huge difference in the destruction of the groomed snow surface outside of the track and in the track.

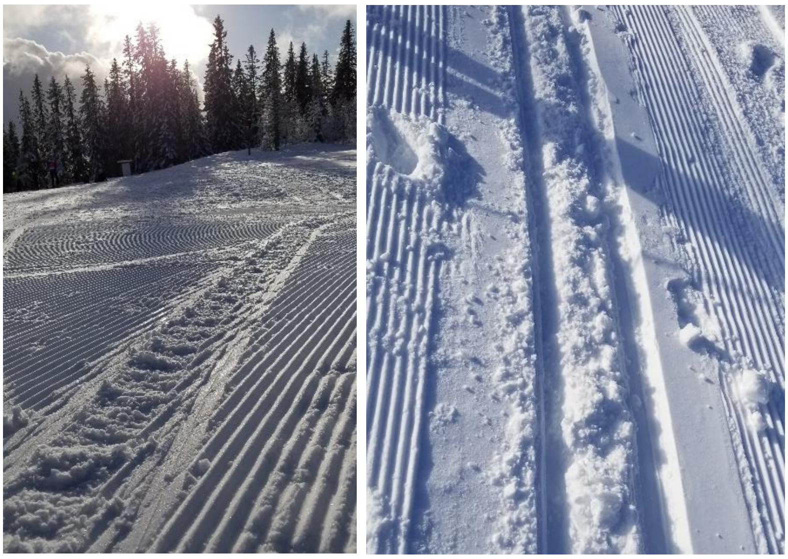

Figure 8: The mark on the trail set by the small wheel prototype outside of the ski track and in the track.

Figure 9: The small wheel prototype and effect of wheelspin on the new snow.

No DP from the user could result in a stop in motion and full slip of the drive wheel. Maintaining power on the motor lead to wheelspin, digging up snow, as one can see from the pile of snow behind the wheel in *Figure 9.*

Bigger contact surface of the drive system and a tread pattern more suited for new snow, made improvements necessary to investigate.

06.03.2020

- Place: Outside of the Workshop, Gløshaugen.
- Conditions: 5 cm, heavy, wet lose snow (not groomed, gravel below).
- Prototype description: Edition 0 of low-fidelity prototype with rubber tracks from a snowblower. Same pivot point in front. Same bottom frame and skis.
- Test objective:
    - The Drive: Pre-test. Reveal hidden design mistakes. Evaluate shaft-to-shaft distance and tension in tracks, gaps or touching between the track in motion and chassis at different depths for the skis.
    - The Sit-Ski: Whether adjustments were needed for the length of suspension bars.
- Result: No or low degree of slip, but much resistance in the heavy snow. Slow. Adjustment for track tension necessary. Much compression of the loose soft snow, both for the rubber tracks and skis.

Figure 10: The track left in the snow by the prototype without the weight of the user.

09.03.2020

- Place: Ferista.
- Conditions: 5+ degrees. Firm, dense snow.
- Prototype description: The first low-fidelity prototype with rubber tracks. Proof of concept. Pivot point in front, on the same bottom frame. With seat, knee and foot support.
- Test objective:
    - The Drive: If tracks function and have potential as a concept. Investigate traction, motion resistance, speed and subjective feeling of the effect of weight compared to other CCSS prototypes.
    - The Sit-Ski: More suited for tracks with additional pivot point under the seat?
    - Ergonomic: Verify added customized parts for knee and foot support and seat. Any discomfort for the user?
- Result: Compared to the small wheel; the tracks had more traction and less impact or destruction of the ski trail, while it had more motion resistance, hence less drawbar pull to assist with propulsion. Better response and less destruction outside of the groomed ski tracks than in the track.

Still the same issue concerning DP utilizing both poles, one tends to lean forward so the tracks lose traction.
Two of three test persons reported discomfort due to humps, the lack of damping in the suspension.
It was experienced that the activity was fun, but more difficult to turn and a bit scary in downhill.

Several aspects with the fidelity of the prototype was present, especially concerning motion resistance and stiffness of chassis. In general, it functioned well although one plate of MDF was destroyed of the drive sprocket. One bolt disappeared from the ski binding. The bracket to a foot support was destroyed, and the foot support was not ideal for all leg lengths. Front suspension bar could have been a couple cm longer. The rubber track could have been more tense. The shaft in the front wheel yielded and was slightly bent.
Knee support and seat was approved for this phase of the development. One belt strap around the waist was used and beneficial, but one or two more straps for the legs should be included in further development.
On the onset of an accident, tilting sideways, the sit-ski chassis turned out to be flexible showing lack of structural stiffness.

Figure 11: The prototype with rubber tracks and its impression on the middle of the ski track.

24.03.2020

Test 1

- Place: Skistua
- Conditions: +4 degrees and rain. Fine, few days old snow, medium firm/loose.
- Prototype description: New drive solution, 26'' wheel with fatbike tire, medium inflation pressure (bigger contact surface and tread pattern more suitable for snow than the small wheel). The frame was similar to the previous test, but new suspension to fit the bigger wheel, working closely behind the user. New hub motor.
- Test objective:
    - The Drive: Assess the effect and change in traction (due to grip and normal force), maneuverability, tractive force, driving force (bigger radius), comfort, etc.
      - compared to the small wheel-concept prototype.
- Result: Very good traction due to other tread pattern and bigger contact surface, compared to the small wheel, even though the normal force on the wheel was lower. No slip, but the tractive force was lower. Slow acceleration. Not helpful starting from 0 km/h and in uphill (too big wheel radius compared to the torque of the motor). Effective at higher speeds. Low motion resistance, also while DP with motor turned off. More comfortable driving over humps (due to air pressure?).

Destruction of tracks were low, only leaving a small mark, as *Figure 13* is indicating. Making the sit-ski to turn, maneuverability, was experienced to be more demanding. Still, a significant effort was needed to maneuver out of the groomed ski track.

Figure 12: The prototype with 26" fatbike wheel in use.'

Test 2

- Place: Skistua.
- Conditions: Same as Test 1.
- Prototype description: Re-test of the small wheel-prototype. ~ 8" diameter.
- Test objective:
  - The Drive: Verify old results and compare to fatbike wheel in the same conditions.
- Result: Confirmed weakness of the concept: Lack of traction lead to wheelspin, full slip, digging a hole and getting stuck even in the groomed trail. (Tread pattern more suited for ice than snow, and very low contact area, while the normal pressure was high and drive force high.)

Figure 13: The tire tracks left on the ski trail from two different drive wheels on the same conditions; test 1 and 2.

On the left-hand side in *Figure 13* is the mark from the wheel with low diameter and studded tires. It experienced some degree of slip; one can say that the shear strength of the snow surface was exceeded by the shear stress from the drive. On the right-hand side is the mark from the prototype with the fatbike tire, which shows that it did not experience slip.

Appendix B

Pre-Master Thesis

NTNU
Norwegian University of
Science and Technology

Cross-Country Sit-Ski –Design Challenges and User Needs

Trondheim, December 2019

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Preface

This report is a result of the Specialization Project of Engineering Design and Materials M.Sc. in the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology, fall of 2019. Project and report is a collaboration of three students.

The purpose of this project is to give an overview of problems and challenges with the cross-country sit-ski design of today, and make suggestions for objectives to explore further.

We would like to show our gratitude to:

Knut Einar Aasland, supervisor

Jørgen Falck Erichsen, supervisor

Norwegian National Team in Para Cross-Country Skiing

NTNU SIAT, Institute at NTNU

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NTNU, Trondheim 10.12.2019

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Abstract

The work of this pre-master is aimed to identify problems and challenges with the cross-country sit-ski (CCSS) design of today in the realm of amateur exercise, not excluding competitive exercise. This project lays the groundwork for a master thesis of Engineering Design.

The CCSS is a sleigh to sit on, mounted on a pair of skis, gaining propulsion by double poling with one's arms. It is sports equipment mainly used by people unable to use their legs for cross-country skiing standing up. In its bare essence it today consists of a seat, leg rests and ski bindings, the structure being fit for personal adjustments to a greater or lesser extent.

Sporting with a CCSS is strenuous, requiring significant arm strength. Users often report little initial sense of achievement resulting in the sport's narrow grounds, yet many are attracted to the idea of enjoying the outdoors and joining friends. To inspire more people to enjoy the sport and the opportunities it provides, the CCSS design requires additions and adaptations, not only lowered weight.

In this report the challenges in design are identified and discussed. Objectives such as forward propulsion, turning, braking and dynamic seating are investigated. Considerable effort is invested in understanding the users and the sport itself through the method of empathizing, testing existing equipment and prototypes. The potential of dynamic sitting position is explored by indoor testing. A CCSS on 4 short skis with the ability to turn is tested on snow. The objectives to take further into a master project are proposed.

Contents

Figures

Acronyms

CCSS	=	Cross-country sit-ski(ing)
DP	=	Double poling
XC	=	Cross-country (skiing)
SCI	=	Spinal cord injury
PWG	=	Paralympic winter games
HR	=	Heart rate
CP	=	Cerebral Palsy

Chapter 1

Introduction

Para Nordic skiing is an activity for people with different mobility impairments to experience the sport of cross-country skiing (XC). It is one of the sports in the Paralympic Winter Games (PWG) where professional athletes from different countries compete. In competition the sport is divided into standing, sitting and visually impaired classes where participants with similar physical disabilities compete against each other. Participants with impairments in the lower part of the body often compete in sitting classes using a sit-ski. The sport itself and the use of a cross-country sit-ski is also a good way for people with physical impairments to experience the outdoors in wintertime with their family and friends and be physically active.

1.1 Paralympic History

Paralympic sports got increasingly popular after the second world war as a rehabilitation tool for injured veterans and civilians. The first Paralympic Games were held in Rome 1960 with competitors from over 20 countries competing in summer sports. It took a few more years before the first winter Paralympic Games were held in 1976 in Örnsköldsvik, Sweden. This was one of the first appearances of Para Nordic skiing in competition and the sport has been a part of the games since then. In the first PWG it was only competed in standing classes, but in the second PWG in Geilo, Norway in 1980, seated competitions with sit-skis were introduced with two competitors [1]. In the 2018 PWG in PyeongChang, South Korea, more than 50 athletes from 14 different nations were competing using a CCSS. [2]

1.2 Equipment

The CCSS originates from Norway in the early 1970 when Vidar Johnsen started to double pole in wheelchairs and pulks. The activity was strenuous and exhausting only available to the strongest users. Handling of the easy equipment was also a problem as it was used outside its application area. Pulks were used in Ridderrennet in the mid 1960s by a limited number of skiers for some years. It was not before the Swiss attached skis to the underside of the pulk, adjusted to the common track width, it became available to the common user [3].

The sit-ski consist of a lightweight, rigid frame with a seat on top where straps and buckles are used to fasten the skier. Two cross-country skis are mounted to the frame in parallel to fit the track. The PWG drives the improvement of the equipment with the goal to go faster and break records. However, the strict rules [4] of competitive adaptive skiing and the limitations set to the CCSS restrain development of new equipment. Most competitive equipment developed for professional athletes focus primarily on weight reduction because of these limitations.

The diversity of disabilities and techniques used by athletes also influence the need for customization of the equipment. The variety in impairments and needs of users results in different sitting positions used. For sit-ski users the main difference is placement of the legs. The different ways of placing the legs are bending them beneath the body, sitting with the knees high or the legs placed straight forward with individual variations. The combination of the strict rules and the high degree of customization hampers the process of finding the best solution to each user.

The accessibility of equipment globally is not very high, especially for youth and their equipment need. The high cost of the equipment is seen as a critical factor for the gap between countries and as an obstacle for beginners to attend para sports. As most products, the development of new para equipment is also affected by the market drives. For para sport the market drive is not high enough to provide equipment for all. [5]

1.2.1 Competitive Equipment

Development of competitive equipment is more prioritized and given more resources than development of amateur equipment. Reduction of weight and optimizing sitting position is usually the focus in development as the rules make room for few other options. In later years, some big companies including Toyota [6], have started mobility projects to develop equipment in collaboration with leading para athletes. The two last PWG in Sochi and PyeongChang Toyota developed a CCSS to one of the best para cross-country and para biathlon athletes, Andrea Eskau. They used new technology from their Formula 1 cars and materials such as carbon fiber to reduce the weight. [7]

1.2.2 Amateur Equipment and Use

CCSS is not just used in competitive settings, it is also a great way for physically impaired to exercise. In modern days the need for physical exercise has become an important part of the everyday life of many people. The need for exercise is not only for the able-bodied, but also for physically disabled, and adaptive skiing is a great way to exercise and a great outside winter activity. [8][9][10]

Exercise for people with limitations often entails additional challenges and require more customized equipment. Most equipment for recreational use is quite simple and primitive as the equipment is based on the restricted competitive equipment. In competitive skiing the CCSS is customized to the specific user. The variations in disabilities and techniques of recreational skiers are as diverse as in competitive adaptive skiing, but the level of customization is not as high. The development of recreational CCSSs have, like the competitive equipment, been focused mostly on weight reduction. However, some adjustment possibilities have also been introduced to cover a wider user group. The sitting position, knee angle, height of the seat, straps and placement of the feet are some of the adjustment possibilities made to make up for the lack of customization. Some manufacturers have also put on brakes on the sleds for recreational use. This is not allowed in competition where skiers have to use their arms or poles to brake. [11][12]

1.3 Mission Statement

The mission of this pre-master is to identify and discuss challenges with the recreational cross-country sit-ski used by skiers with physical limitations. The pre-master is exploring the potential and possibilities of the CCSS design in an attempt to make the sport more attractive and inspire more people to enjoy exercise in the outdoors.

The relevant theory to this project is presented in the next chapter before a description of the work conducted in this project comes in chapter three. The findings from the work are given as key improvement points in chapter four, discussed thoroughly in the fifth chapter and concluded in the last chapter. The project should work as a background for a master thesis of engineering design where further development is to be conducted.

Chapter 2

Theory

The topics of methodology, rules, attributes and physiology are to be covered in this chapter, as well as sitting position in CCSS.

2.1 Product Development Methods

Several approaches can be used for engineering design projects. A wide specter of models have been developed to guide through the process. They can be seen as guidelines to follow or inspiration. Two methods are briefly described below.

2.1.1 Ulrich and Eppinger

The method of Ulrich and Eppinger is a practically-oriented product development approach. Not only relevant for development of comprehensive products in organizations, but also development of sub-systems for project teams. While initially having a wide set of concepts, the alternatives will be narrowed down, and the product getting more specified and detailed by each step. As shown in figure 2.1, the generic product development process is divided into 6 phases divided by milestones. [13]

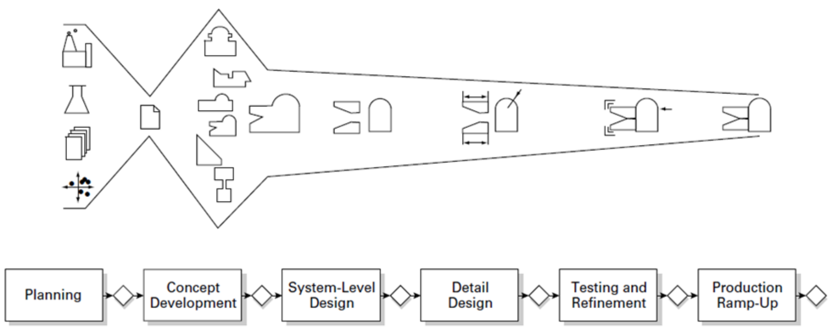


Figure 2.1: The generic product development process, Ulrich and Eppinger [13].

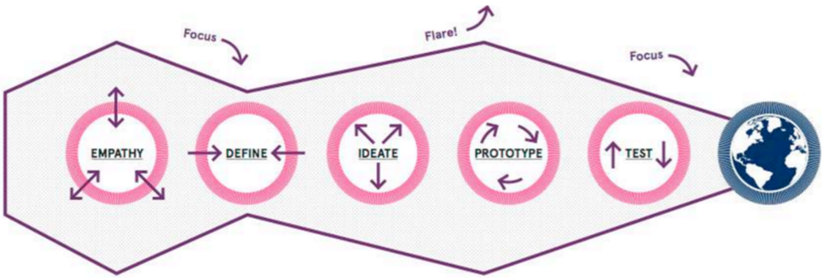


Figure 2.2: The design thinking process [14].

2.1.2 Design Thinking

The method of Design Thinking represents a multidisciplinary and user-centered approach and is applicable early in the innovation process. Several models exist to describe the process, but none are very detailed [15]. The process can be visualised linearly, as in figure 2.2, but in practice, a typical process will have several iterations. Focus on empathy and feedback from users are maintained throughout the process, the tool of empathy being an essential quality of the model. [14]

2.2 Empathizing

In product development, empathizing is the process of understanding the end user's needs, how they think and feel. It is an important part of Design Thinking, suggested as the first phase of the process in figure 2.2. By seeing the world through the user's perspective, developers can feel unity with the user and discover needs. Understanding the needs and making them into specific requirements for a problem guides solutions for designers. Empathizing can help developers come up with new ideas because it forces them to look at a problem from different angles. [16]

Empathizing use different methods to gain insight and create the best product to cover the needs. Some of the methods will be descried in short; interviews, also with extreme users, observation and bodystorming.

2.2.1 Interviews

One of the most used methods of finding customer value is by identifying what the end users are saying. Interview in this sense also resemble everyday conversation, but are focused on requirement of data. Interviewing is an effective way to gather needs, hopes, desires and goals by interacting and listening to what end users say. This gives developers an improved understanding of problems and needs of the users. The method is a way to learn about the end user and what outcomes they expect of the product. It can also be used to get the opinions, attitudes and an explanation on how customers use a product. The interviewing method is very useful in improving or upgrading products, but for novel product development the customers do not always know what they want. Observation can therefore be used in addition to interviews to get a deeper understanding. [17][18][19]

2.2.2 Extreme Users

Engaging with extreme users can provide deep insights other users may be unaware of. Extreme users are users that exhibit sharpened traits compared to mainstream users. It can also be people within the organization in direct contact with the users aware of expectations and unmet needs. The purpose of including extreme users is not to develop solutions specific for those users, but to identify problems mainstream users have trouble voicing. Some of the specific problems experienced by extreme users may not be relevant for mainstream users, and developers should focus on needs found in all users. These needs and problems have a tendency to become magnified in extreme users. If a product manage to please an extreme user, it should keep the more mainstream user content. [20]

2.2.3 Observation

To truly understand the need of the end user, observing them is a useful approach. Optimally, all concept development cycles should start with observations of the user in the right habitat. Interviews will not necessarily unveil all unspoken needs, and observations may reveal unexpected insight that can be useful. Observing is not limited to finding user needs, but it is also possible to get a peak at competitors or expose other coming problems. In right conditions, this can be a powerful tool and be helpful if you don't know which problem you are trying to solve. If this information is treated right, it can be used to invent a novel product that fit the user's life by fulfilling an unmet need. [18][21]

2.2.4 Bodystorming

A step further than observation to obtain insight in the problem is bodystorming. Developers can take part in physical testing and experience a situation to unmask problems and generate new ideas. By putting oneself in someone else shoes and immerse in the user's environment, developers can obtain empathy and insight. Unexpected problems and solutions may be found and used to find the most fitting solutions. [22][23]

2.3 Prototyping and Prototypes

Prototypes are, according to Ulrich and Eppinger, "An approximation of the product along one or more dimensions of interest" [13] and is an important part of product development. Prototyping is the process of making these approximations. It is used for validating and verifying assumptions as well as being an inspiration and a way to convey ideas in groups. Prototyping can also lead to increased knowledge about unknown elements of the product.

2.3.1 What Prototypes Prototype

By identifying important open design questions, prototypes can have a clear focus to communicate different solutions. Houde and Hill [24] highlight the importance of a clear purpose of the prototype. They describe prototypes in terms of their function by dividing them in three dimensions; *Role*, *Look and feel* and *Implementation*, visualized in figure 2.3. The *Role* prototype investigate what a prototype does for a user and describes functionalities users benefit from. *Look and feel* explore and demonstrate the concrete experience of the prototype, how it is to look at and interact with. The *Implementation* dimension answer technical questions about how the product should work and discover adequate specifications for the final. When the prototype shows the complete user experience it is called an integration prototype.

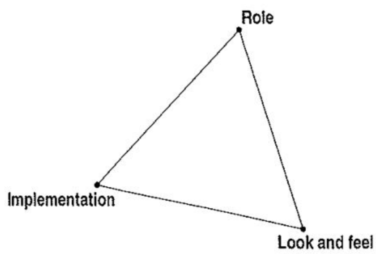


Figure 2.3: What Prototypes Prototype [24].

2.3.2 Experience Prototyping

Close to the *Look and feel* dimension there is a prototyping "method" defined by Buchenau and Suri called experience prototyping [25]. With active engagement of prototypes, existing solutions from competitors or situations, it is possible to gain first-hand experience on how it will be to interact with future products. However, experience prototyping goes beyond the *Look and feel* dimension. The active engagement give insight about the *Role* of the prototype and what the product does for the user. This means that any kind of representation designed to understand, explore or communicate what it will be like to use the product, system or space can be seen as experience prototyping.

2.4 Rules

The rules governing CCSS competitions allow little freedom of design. Maximum seat height is defined as 40 cm between buttocks and top of skis [4]. In addition, the rules demand the seat to be entirely rigid. The two points mentioned are the most relevant for this project, found in the World Para Nordic Skiing Rules and Regulations 2017/2018 under section 224.7.

2.5 Attributes

2.5.1 Span Curve on Skis

To distribute the weight of the skier to the snow over the entire length of the ski, the ski is constructed with a camber profile, as seen in figure 2.4. The span curve will be unique for every XC ski and show a greater height around the middle of the length, due to its stiffness, having big impact on the glide and qualities of the ski [26]. Skis for skate and classic technique, cold and wet conditions, and competitive and recreational use will all have a different span curve more suitable.

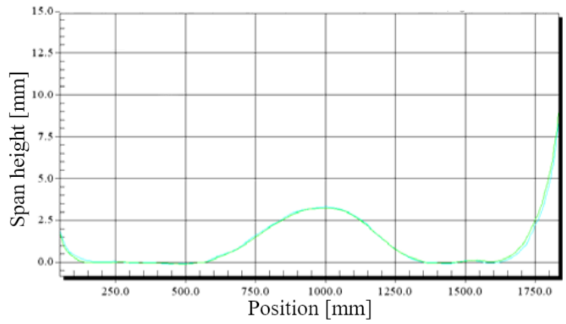
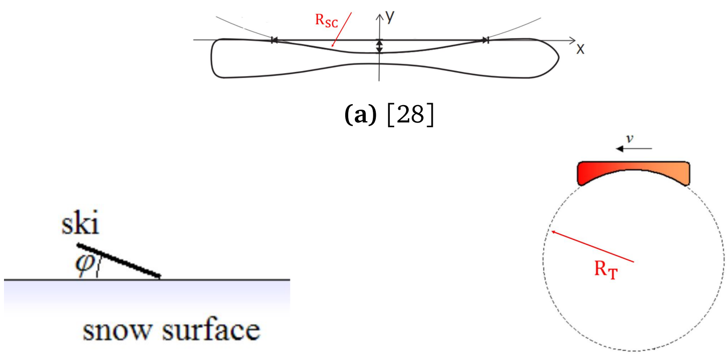


Figure 2.4: Measured span height over the length of a pair of skate skis [26].

2.5.2 Carving

Carving skis are skis manufactured with side cuts such that the front and rear of the ski is wider than the middle. See figure 2.5; if φ is zero, a pure carving turn will have the same radius R_T as the ski's side cut radius R_{SC} [27]. The principle is commonly used in backcountry and alpine skiing for decades. Some XS skis also come with some degree of side cut e.g. Madshus 119 Nanosonic (44mm-41mm-43mm).



(a) [28]

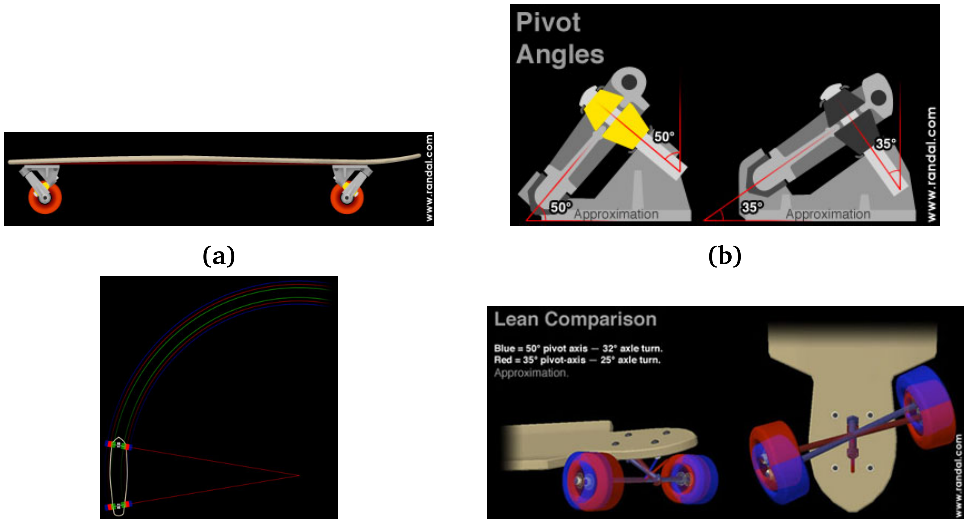
(b)

(c)

Figure 2.5: Carving skis [27].

2.5.3 Skateboard Truck-system Mechanism

To turn while riding a skateboard one leans to either side to tilt the deck, the bushings are then compressed and force the hanger to turn. The track of one wheel is now shorter than the other, and thus the skateboard's path is curved, see figure 2.6. A high pivot angle yields a smaller radius turn per degree deck tilt. [29][30]



(a) **(b)** **(c)** **(d)**

Figure 2.6: Skateboard trucks and turning [30].

2.5.4 SkiErgometer

In multiple outdoor endurance sports, ergometers are used for training and testing purposes, as they continuously measure the work performed in the exercise. The SkiErgometer is an ergometer simulating double poling and therefore an important tool for out of season training when ski trails are not available. Research [31][32] have shown that laboratory testing with DP ergometer is similar to a field test if evaluating peak VO_2 in elite cross-country sit-skiers.

2.6 Physiology

Para sports are exercised by people with many different sorts of limitations or disabilities. This is also the case in adaptive skiing where people with a wide range of disability can partake in the activity. Users with severe limitations to the lower parts of the body are not able to use ordinary cross-country equipment and are directed to use a CCSS. The most common limitations of these users include spinal cord injuries (SCI), amputations and cerebral palsy but also users with other kinds of limitations use this equipment.

Spinal Cord Injuries

SCI are injuries caused by damage to the spinal cord from trauma, degeneration or disease. The degree of paralyzation, the control of arms, legs and body and if sensory loss is partial or complete depends on the location and severity of the injury. The location of the injury is related to the different sections of the spinal cord, cervical, thoracic, lumbar and sacral. In this project only the thoracic, lumbar and sacral injuries are included and referred to as high, mid and low SCI. [33][34]

Amputation

Amputation is the process of surgically removing a part of the body such as a limb. In Norway, the majority of amputations are lower limb amputations. Most of them are caused by poor blood supply as a result of diabetes, often on an elderly patient, but up to 15-20% are caused by injuries from trauma, cancer, burn damage and infections. People with lower-limb amputations are usually required to use assistive devices such as prosthesis, crutches or wheelchair. [35][36]

Cerebral Palsy

Cerebral Palsy (CP) is a neurological disorder. It is a lifelong condition affecting muscle coordination and movement. It is caused by a problem in development of the brain before, during or soon after birth and causes a range of disabilities. The term is quite wide with varying degree and is unique and individual to the person affected. [37][38]

2.7 CCSS and Sitting Position

The sit-ski, because of the individual needs, is custom-built or made adjustable to fit the individual user. The fitting process is time consuming with many possible adjustments, and the fit should be snug, secure and comfortable. This is to transfer most of the power from the skier into forward movement.

The height of the seat is dependent on what disability a user has. It should be high enough to support the highest group of muscles with paresis or plegia to users with SCI. A too high seat will on the other hand limit the movement and affect the balance.

Braking and in some cases turning is done by touching the ground with both or one hand and the frame must be low enough for the user to do this. A lower frame also makes it easier to right the sit-ski after a fall and enhances control.

2.7.1 Sitting Position

In the CCSS, there are different ways of positioning the body of the skier depending on the disability and the skiers skill level. The positions can be divided into some variations of sitting and knee-standing, as seen in figure 2.7. Which position to use is decided by the individual user. The angle between the torso and femur can be used to describe the difference between the positions.

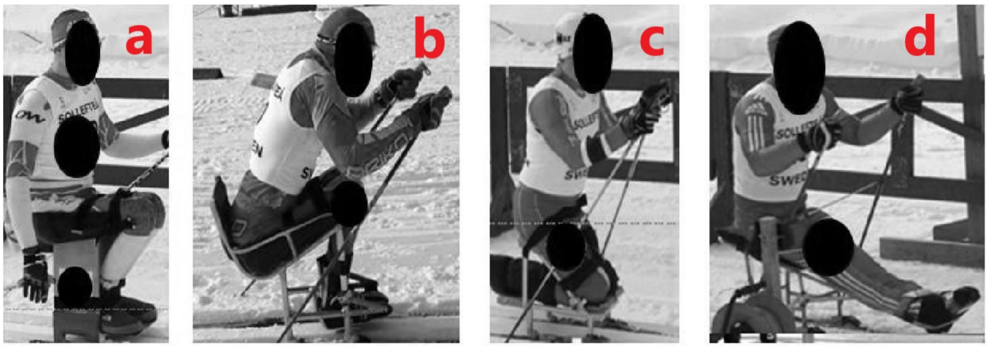


Figure 2.7: Various sitting positions [39].

In picture (c) in figure 2.7 a knee-standing position is shown. The angle between the femur and torso is obtuse when the skier is upright and the feet are bent beneath the body. Knee-standing is a powerful double poling position [40] where the user can move dynamically. It is used by people with full core function or experienced skiers with low SCI. [41][42]

The neutral sitting position is shown in picture (a) and (d) in figure 2.7 with the feet either placed forward or bent down in a chair like position according to the user's preference. Sitting with bent legs are most common among users with low to mid SCI. The neutral position is the most common and is usually the starting position for beginners. It is more stable and more comfortable than the knee-standing position. Though it is not as powerful as the knee-standing position the user is still able to generate a lot of power. [41][42]

In the sitting position in picture (b) in figure 2.7 the athlete sits in an angled back position where the hips are below the femur and the angle between the torso and femur is acute. The position provides greater stability to the upper body and more spinal support. It is recommended for users with higher SCI because of increased support. The position serves three purposes for the user. Users with little to no core function is kept in an upright position, and the position improves circulation and reduces spastic contractions. In this position the hips are forced back and give a more secure fit. For users not in need of the extra stability, the position is not recommended because it limits the mobility and reduces use of the core strength leading to a less powerful poling movement. [41][42]

Influence on performance

In Paralympic competitions there are time compensations based on class [43] adjusting the result to account for how the different disabilities affect performance. A study by V. Rosso et. al. shows how the level of disability influence athletes' performance [44]. The study investigated how the trunk function affects the motion and force in propulsion. It concludes that skiers with more trunk control have a greater range of motion during the poling motion and therefore generating higher propulsion force.

The different sitting positions used in CCSS were researched in an article by Ohlsson et. al. show that the position of the skier also affects performance to some degree [40]. Different studies with both able-bodied and disabled athletes have investigated how sitting positions influence VO_2 consumption, HR, etc. [45][39]. All studies conclude that the knee-standing position is the most effective, while the worst is the angled back position with a disadvantage of as much as 15% when translated to time [46].

Chapter 3

Method

In this chapter, the means and methods utilized to understand the sport, the athletes, the CCSS design and its challenges will be described.

After the mission was stated, the work of the project has mainly been in the phase of concept development, as in the generic product development process shown in section 2.1.1, to investigate the possibilities of developing a new CCSS.

3.1 Empathizing and Gathering User Needs

Placing oneself in the user's position is a good trick in product development to better understand where the shoe pinches, as described in section 2.3. Much and diverse effort has been made to unfold the situation of the sport, the users and the design; Interviews made with leaders, amateurs and top athletes with wide ranging handicaps. Testing different CCSSs, and comparing the real physical designs on the market, as well as hours spent on a commercial CCSS for testing on a treadmill. Speaking with manufacturers and retailers. Testing equipment from other para sports.

3.1.1 Testing Hand Bike

A hand-pedaled bike was acquired to get a feeling of curbs, visibility and sight, hills and road quality, traffic and people's consideration of unusual sports equipment. The experiences, though made with another sport, were valuable universal learning; one is close to the ground and must therefore take extra care in ensuring one is seen. The equipment demands thorough road planning in terms of turns, potholes, curbs and road width. Other road users do not well evaluate one's movement pattern, and so one is often forced to slow down or stop inconveniently.

3.1.2 CCSS on Rollerski Treadmill

To get a deeper insight into the sitting DP technique and requirements, a research project was joined as a volunteer to get a few hours in a CCSS mounted with rollerskis on a big treadmill. Two workouts of more than an hour with incremental and all-out tests were completed. Even after several years of experience as a competing cross-country skier double poling some of the world's longest races, sitting in a CCSS was necessary to fully immerse oneself into technical requirements. In traditional skiing, when double poling, one can utilize gravity by falling forward and flexing the core muscles to get an effective and economical technique using the entire body. Compared to standing DP, it was not as beneficial to lean forward, so the smaller muscles of latissimus dorsi and triceps became the main contributors. Hence, the athlete's maximal oxygen consumption was lower and muscle capacity restricted the speed. With low gradient on the treadmill, a speed of 21 km/h was reached, resulting in a wish of having longer arms and jumping out of the CCSS with a claustrophobic feeling. When the workout was completed after 90 minutes strapped to the CCSS, the knees were sore and the legs were hurting more than the upper body. Lessons were learned and ideas of improvements for a better experience in a CCSS were made.

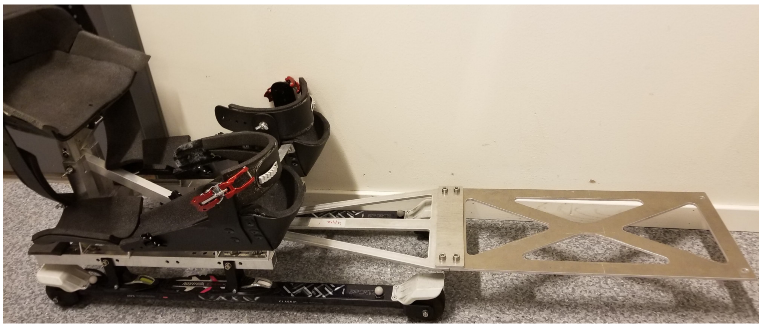


Figure 3.1: The CCSS with Rollerskis used on the big treadmill. The plate in front was connected to an aluminum track for safety.

3.1.3 CCSS with Rollerskis

While the ground outside was still bare, different models of CCSSs mounted on wheels were tested, as seen in figure 3.2. In lack of snow, rollerskiing will be as close one can get to cross-country skiing.

Commercial models available through NAV were tested in September south of Trondheim. While on the treadmill one has no change of direction, skiing outdoors requires more maneuvering. Having the CCSS mounted on rollerskis it showed almost impossible to make turns, which is troublesome for the user, feeling lack of control around cars and other obstacles. Circumstances constrained the testing to the parking lot and one slope. Much planning was required before downhills as one did not manage to turn. Turning was only achieved using the poles to lift the body weight and rotate the CCSS while standing still. Luckily, the CCSS tested in downhills were mounted with a braking system, so it was possible to slow down. In total, including the heavy efforts to DP uphills, this equipment was not a pleasurable means of exercise.

Figure 3.2: Uphill DP in a commercial CCSS with rollerskis.

Exero's Spike is an alternative to CCSS on rollerskis; an exercise product on wheels with a satisfactory steering system for knee-standing DP. Spike was tested in action, and with a feeling of control in the turns and downhills, a good experience was obtained.

3.1.4 CCSS on Snow

Two commercial CCSSs were tested in the ski trails. The sitting positions of the models were knee-standing and neutral sitting with legs forward. Having legs forward resulted in a DP position leaning backward and was experienced to be extremely demanding for the arm muscles. One thing was the heavy work required to get propulsion up small hills, but turning and maneuvering were also difficult. It was experienced that much core and abdominal strength were needed for maneuvering in and out of the tracks. Testing was conducted by able-bodied people, but it is sure to assume the strenuous feeling is transferable to individuals with physical limitations as well. The knee-standing CCSS was a bit easier to handle and one had more power for propulsion as it was possible to lean forward and activate the abdominal musculature. However, the equipment itself felt heavy and required strenuous work.

3.1.5 Interviewing

In section 2.2.1, interviewing is described as an effective means of gathering spoken customer needs. By listening carefully, much useful information from users was collected. Three types of user groups were interviewed, all with different perspectives.

Extreme Users

As described in section 2.2.2, one can listen to extreme users with unique insight, people who have several years of experience as well as taken part in developing equipment. One of few valuable assets like that is Trygve Larsen, seen in figure 3.3. He has participated in the World Cup for a period of 12 years and is one of the pioneers of the sport [47]. He had many thoughts on how the equipment should be, naturally from the perspective of a competing top athlete. Minimization of weight was the key, according to Larsen. A lightweight CCSS is more responsive and easier to maneuver, which is important to enjoy the sport. Throughout his career, he focused on moving the pressure point as close to the ground as possible. His solution was to lean forward, as to allocate most of the bodyweight on the knees, to a point on the CCSS closer to the ground. This way the line of action resulting from his body weight goes downwards in a rather straight line via the sit-ski to the skis, the pressure onto the skis being more focused. Having the seat carry much of the bodyweight one is balancing higher off the ground with less control.

Another CCSS athlete was interviewed in Levanger, which provided insight into the challenges of wheelchair users and sit-skiers with impairments. It was stated that the muscle group experiencing most fatigue was the back. A need to work out and ski with able-bodied friends, was reported, this being exhausting with the CCSS equipment of today. Due to the same reason, the activity of hand biking was preferred since it would able him to keep up with the pace of training partners.

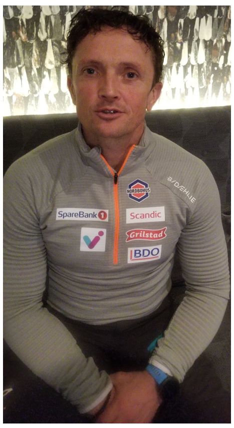


Figure 3.3: Elite para-skier Trygve during our interview in Drammen.

Amateurs

An important user group, often with essential and unsolved needs, is the novice users and amateurs. Facing many of the same challenges as athletes, but without the years of specific training and resulting strength, they represent a group of significance for recruitment to the sport.

The number of people identifying themselves as sit-skiers is strictly limited in Norway. One user was interviewed. The uphills being too heavy to DP continuously, it was reported that hardly any sense of achievement was felt through the activity of CCSS. Transportation from the car to the start of the ski trail could be a problem. This resulted in a lack of want to begin new CCSS workouts.

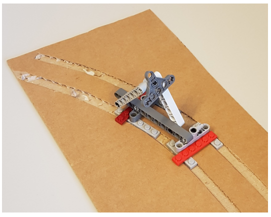
Leaders and support

Coaches and support personnel might not be users directly, but after years in the CCSS community and communication with athletes, they have much interesting insight and an overview of the field. Two leaders for the Norwegian national team in para XC skiing were interviewed. Among other things, it was focused on how to involve more users in the sport. In traditional ski trails, it might be too physically demanding to DP the steep uphills and the downhills too challenging to feel safe. Hence, many users struggle with lack of motivation. The activity is too burdensome and tiring for recreation and limited to easier trail systems. Help with propulsion and downhills will make it easier to motivate oneself and include a wider range of users. The seat height and point of gravity were also discussed with regards to improving the maneuverability. In competitions, much time is lost in technical sections of the course due to lack of confidence. It was pointed out, for training purposes, that several modifications on the CCSS are acceptable as long as the sitting position remains identical to the one used in competitions.

For the national team, an additional important matter of improvement was the pressure point on the skis to optimize glide and control, as described in section 4.6. In general, the leaders of para skiing in the Norwegian Ski Federation had much knowledge to share regarding the present challenges of sit-skiers.

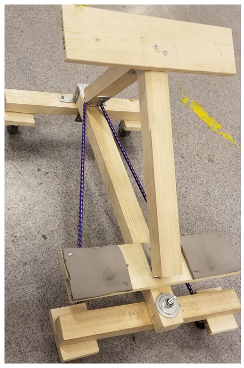
3.2 Investigating Turning

The concept of *4 skis and pivot point* was initially demonstrated in a prototype using Lego, see figure 3.4. Next, a full-size prototype on wheels is made out of wood. A pivot point in the front is then introduced. The rear and front of two normal XC skis are cut off and used as short skis. As bindings, a piece of wood is glued onto the ski, further attached with a metal bracket, figure 3.5.



(a) First prototype, pairwise parallel skis, central pivot point in front.

(b) Full-size prototype knee-standing position, on wheels.



(c) Prototype modified, pivot point.

Figure 3.4: Prototyping steps without skis.

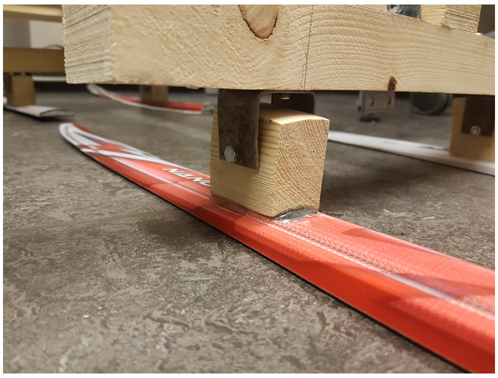


Figure 3.5: Prototype with skis, binding.

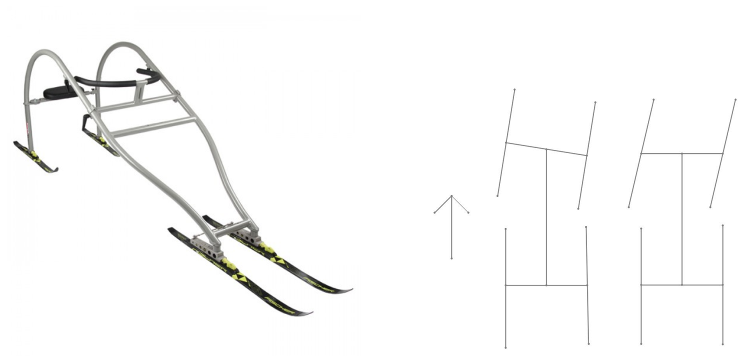
3.2.1 Alternative Concepts for Turning

Skateboard Trucks

Skateboards turn when tilted, as the wooden plate is mounted on *trucks* at an angle of 45°, as described in section 2.5.3. The user is to lean in the direction of the curve making the front skis turn accordingly. This concept is based on the idea that turning is induced by the user and the front skis point forward otherwise. This concept has yet to be materialized in a prototype.

Two Pivot Points

The front skis of the BeitoSkilator can turn, notably by two pivot points one over each ski, as opposed to one central pivot point, see figure 3.6. A transverse rod keep the skis parallel. The skis are assumed to carve into the edges of the trail in a curve with a large radius, where with one central pivot point the skis will not touch the edge. Two pivot points is more complex than one. This concept has yet to be materialized in a prototype.



(a) **(b)**

Figure 3.6: BeitoSkilator and its principle of turning demonstrated in the rightmost drawing [48].

3.2.2 Testing Prototype

The prototype in figure 4.4 was tested on snow in prepared ski tracks in somewhat flat terrain. It was tested alongside two commercially available CCSS, as described in section 3.1.4. The aim was to feel and experience the prototype itself, with the opportunity to cross check with the quality available on the market. The objectives to be observed and experienced:

- Turning; forced and following tracks
- Sitting position
- Centre of gravity
- Glide
- Sideways tilting and balance
- Stability
- Downhill
- Skidding
- Surprises

Figure 3.7: Testing prototype in ski tracks.

3.3 Investigating a Moving Sitting Position

A potential long-term goal was to utilize movements of the body mass during DP in a CCSS to create an additional force to help forward movement on the snow. Further research was needed to investigate if this motion could be converted to aid propulsion and where the energy would come from. Learning was necessary to reduce uncertainty of the concept and simple models were made to explore possible solutions. The purpose of the prototypes was to investigate the ski-technical feeling and experience of the concept, like the idea of *Experience Prototyping* described in section 2.3.2. Changing the rigid seat of the CCSS into a flexible one will change the technique and several parameters.

3.3.1 Simple Models in the Workshop

Spring Model

Some athletes struggle with back pain and have experienced more fatigue in back muscles than abdominal muscles during DP workouts, as mentioned in section 3.1.5. These athletes could need help in the part of the DP cycle when the back is lifted. One of several solutions possible is a carbon fiber composite plate working as a spring by connecting the seat to the front of the CCSS where the knees are. This would make the seat flexible creating a force on the body. This type of directional force might assist with DP in CCSS if created expedient. However, a solution like this would not be accepted in CCSS competitions, as mentioned in section 2.4, but is worth exploring as the development of training equipment is not restricted by the rules.

Figure 3.8: Testing of the *Spring Model*.

A simple model working in a similar way was made using a rubber band. As a system with a spring assumed to have no energy loss, a rubber band was used to create a pulling force pointing upwards under the seat, as seen in figure 3.8. The rubber band was connected to a table with force in vertical direction lifting the body during simulated double poling. The length and number of rubber bands were varied, resulting in different sitting heights and magnitude of upward force to the seat. A feeling of the concept regarding DP technique was obtained.

Damper Model

To further investigate how a momentum of the body in a DP cycle could be utilized, models with a seat post damper were made.

The concept model consisted of a height-adjustable seat post dropper from a bicycle that would determine the height of the seat. It could be kept at a constant length or functioning as a damper dependent on the gas pressure. The damper was installed under the seat and connected to a joint on floor level. The force of the damper, working upwards under the seat, was to be compressed with gravitational and human power, illustrated in figure 3.9. In a DP cycle with the post working as a damper, the damper would first be compressed and then released. This changes the height of the seat causing a dynamic sitting position.

The starting position of the cycle is a low seating position with the damper compressed. When the skier pushes the poles down and back, some of the mass is lifted and the damper is released. This elevates the seat and lifts the skier up leading to a rotation of the knee. After the push movement, the skier leans back and compresses the damper and returns to the starting position.

Figure 3.9: First physical representation of the *Damper Model* with a seat post.

3.3.2 Testing the Damper Model with SkiErgometer

To gain further understanding of how a movement with damping in the sitting position is impacting the DP power output, a simple test with a SkiErgometer (Concept2 Inc., Morrisville, Vermont, USA) was constructed. The physiological aspect is very specific and close to the CCSS DP movement with the SkiErgometer, as described in section 2.5.4. Hence, executing a test with the ergometer would be useful without a ski trail available. Before the test was performed, the concept model was made into a test rig to simulate and substitute a CCSS and the movement that should be investigated, as seen in figure 3.10.

Figure 3.10: Test person 1 in action.

The Experimental Procedure

The sequence started with 10 minutes of activity on the SkiErgometer to warm up and get used to the equipment with correlating new versions of the DP technique [49]. Two tests were executed for both participants. One for each type of sitting position. To reduce the number of variables in the test, the intensity measured as heart rate (HR) average was aimed to be kept constant. Since HR is influenced by several parameters and might increase over time at the same power, the measurement did not start before one minute of continuous DP had passed. A pre-defined workout was customized on the display of the SkiErgometer computer, so average HR and DP frequency would be saved in the memory of the computer. Both participants performed the test on the same subjective intensity and SkiErgometer resistance (5 on model PM5). Then, the test rig was changed to a rigid seat pin before both participants repeated the exercise. HR monitor and SkiErgometer computer were recorded. An additional guest athlete also tried both test rigs to obtain a meaning about the concept.

Test Results

The test with SkiErgometer resulted in the following data, with power outputs displayed in Watts.

Test	*Person*	*Watt*	*HR avg.*	*Frequency (s/min)*	*Sitting height (cm)*
With damper	1	107	110	32	36
With damper	2	78	154	37	36
Without damper	1	122	110	31	49
Without damper	2	82	155	44	49

Table 3.1: Numerical results of the SkiErgometer test

Chapter 4

Key Improvement Points

The potential and challenges of today's CCSS are to be identified. Users and even the sport's top athletes report CCSS a strenuous activity. One might be robbed of the sense of achievement and feel dispirited after the initial tryouts. Nevertheless, CCSS provides the opportunity to enjoy the ski trails and the crudity of self-induced propulsion on skis. These are reasons to encourage further development of the sport, making it more accessible to various impairments and age groups.

An overview of the situation going skiing in a CCSS is given in figure 4.1. The equipment must fit in the car, the skis must be mounted, the user must be properly seated, the ski trails must be suitable, balance is a challenge and one might want supporting propulsion.

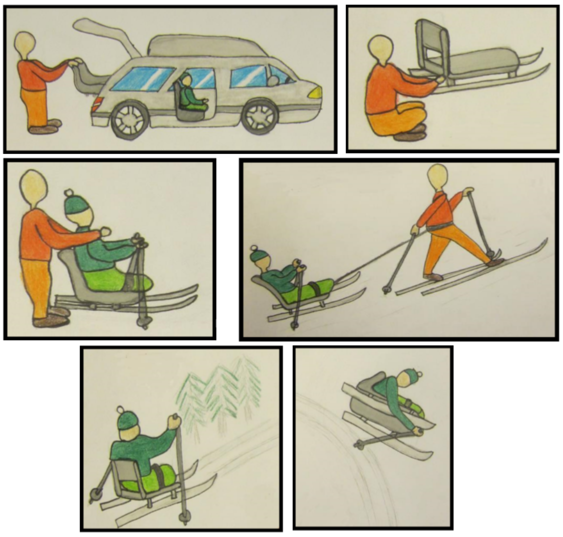


Figure 4.1: Storyboard [50].

CCSS is a demanding sport and has to be exercised in appropriate terrain. The trail maps for the World Para Nordic Skiing World Cup 2019 in Lillehammer (figure 4.2) show the trails for sitting and standing athletes differ, see appendix A. The trails for sitting athletes involve considerably less climbing and decent, and tend to have longer portions of rather straight path. For exercise, users in general return to the same trails they know are feasible. Recreational users may not have the same facilities and are in some terrain types and snow conditions in need of assisted propulsion. If needed, this is done by getting pushed or dragged by a helper.

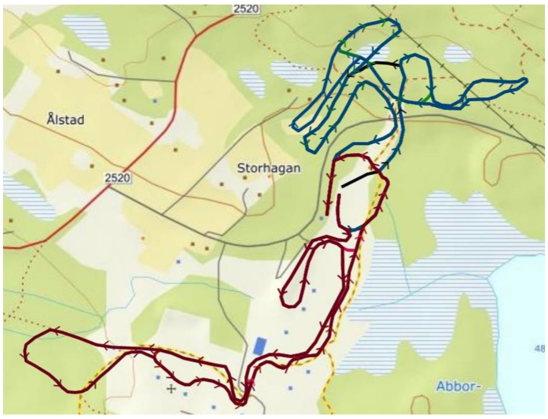


Figure 4.2: Trail map for the World Cup in Lillehammer December 2019, 3 km. Red color for sitting athletes and blue for standing.

4.1 Propulsion

Propulsion is strenuous in CCSS. The physique of the users varies widely, and some athletes are prevented from using their abdominal muscles relying entirely on their arm strength. The silver bullet is a solution allowing the traditional double poling movement that also provides some assisted propulsion, yet preserving the exercise aspect. A solution attending to all the objectives mentioned would make the sport more available to a greater audience. Steep hills and long routes might be rendered harmless. It could be argued the benefit of the exercise is reduced, however, studies on electric bikes promote the significance of the activity attained nevertheless [51]. People might refrain from any activity with the sports equipment if it is too strenuous, and so the profits of activity makes up for the energy spent by an extracorporeal source.

For manual wheelchairs there exist motorized attachable fronts, see figure 4.3. The concept of a motorized attachment might be transferable to CCSS.

Figure 4.3: Wheel-e, motorized attachable wheelchair front [52].

4.2 Turning

Two situations are in question when referring to turning, turning on the spot and turning while in motion in the trail. The CCSS of today, rigid structure on two normal length skis, demands turning to be tackled predominantly by the arms. To turn on the spot, one lifts oneself by both poles firmly planted on the sides and twist the body, as earlier described. In motion, athletes portion their incoming speed, lean into the turn with the upper body, and compensate with frequent poling and light jumping in order to follow the curve. Were the CCSS design to better tackle turns and gradients, users would have more freedom in choosing trails and joining able-bodied friends.

4.2.1 Pivot Point and 4 Skis

Turning may be inspired by snow carts and skateboards. Their common denominator is a pivot point and separated rear and front. Today all CCSSs are mounted on 2 skis, be it mounted on 4 shorter skis the front may move independent of the rear.

To explore the idea, its potential and behavior on snow a full size prototype was built. The prototype is a wooden knee-standing position CCSS mounted on 4 short skis cut from normal XC skis. The skis in the front are mounted in parallel, connected to the remaining structure via a vertical bolt acting as pivot point, see figure 4.4. More on prototyping and testing in section 3.2.

4.2.2 Carving Skis

If the tip of the ski is wider than the middle, the ski will follow its curve when slightly tilted and pressured, as described in section 2.5.2. Pronounced carving is more commonly seen in alpine skiing, however, some carving is also found on cross-country skis. Within the limitations of the trail width, a tiltable CCSS mounted on carved skis could make it easier to follow the trail through turns, see figure 4.5.

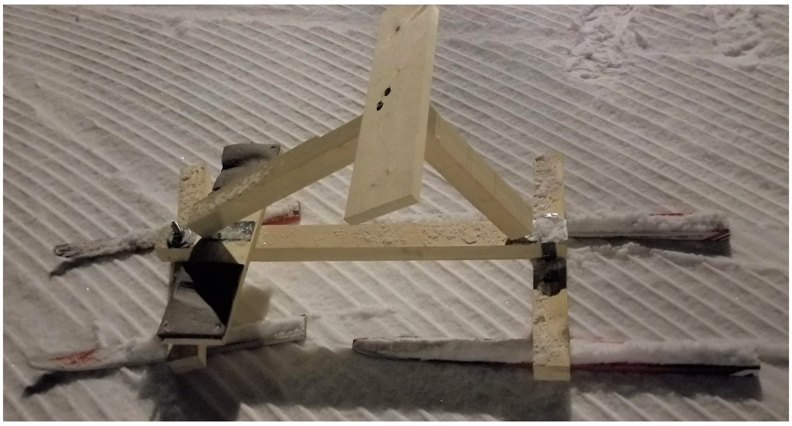


Figure 4.4: Prototype exploring turning. Vertical bolt acting as pivot point to enable rotation of frontal ski pair. A spring is connected to make forward the preferred direction.

Figure 4.5: Tempo Dualski by Tessier with closer look at the tilt enabling mechanism [53].

4.3 Adjustable Point of Gravity

Seat height is constrained by the world para Nordic Skiing rules and regulations [4], which also demands rigid seating. The national team has in conversations uttered a strong wish to keep the seating position unaltered. Their wish can be interpreted as most applicable to top-level athletics and of less importance for amateurs. Going down a steep slope, a low center of gravity is preferred, while double poling uphill one prefers a higher position as it is assumed to give higher forward propulsion. Where one would prefer the pressure point along the skis might also vary. It has been hypothesized whether a dynamic up and down movement of the seat would feel better in use, and whether the motion could be utilized beneficially. A prototype was built to test the potential of the concept, see more in section 3.3.

4.4 Braking

In competitions no moving parts, including brakes, are allowed [4]. However, brakes provide security assurance in normal ski trails. Braking is commonly done with the hands or the tip of the poles down in the snow along the side of the body. Some CCSSs on the market have incorporated brakes as can be seen in figure 4.6. The way to decrease speed while gliding on snow is to grasp the snow, digging into it. The question is then; which part of the track should be sacrificed and how to cause the least damage? Tracks are reshaped regularly, however, to avoid social shunning and negative association, a solution that does not destroy the tracks is preferable.

The CCSS may however cause damage to the tracks if the damage is corrected thereafter. Were the snow grasping object to be placed in front and the correcting object after it. The brakes might grasp the track itself in the front, mending the damage by sliding over with sufficient pressure. Another example; the brakes could be shaped such as to mirror the track. Braking outside of the tracks might then be reduced.

Figure 4.6: Brakes on Tessier's Eskaip [54].

4.5 Ease of Getting In and Out

Getting seated in a CCSS without any help can be challenging and is closely linked to the individual impairment. As can be seen in figure 4.1, managing the whole situation single handedly might be a challenge extending beyond the CCSS alone. However, paraplegic users have expressed wishes for something analogous to detachable handles on the CCSS. Were the seat of the CCSS at the same height as the wheelchair seat it would be easier to position oneself, according to the mentioned users. The CCSS should hold its stable position while the user is getting seated, imbalance and sliding should be avoided. Fastening of skis and straps should be manageable by the user alone.

4.6 Pressure Point on Skis

Today, the weight of the CCSS falls mainly on the rear part of the ski, not the point a ski is constructed for, which reduces the glide. In conversation with the Norwegian national team the issue was pointed out, as the skis and bindings used are the same as for standing users. The chance to follow the evolution of regular XC skis was expressed as an advantage desirably kept. It was though perceived advantageous moving the pressure point forward. This is now limited by how the fixed position of the NIS plate onto which bindings are mounted. Making holes for alternative CCSS bindings is generally avoided as it expectedly tampers with the ski's camber. The foam core is not considered particularly suited for fasteners.

Madshus manufactures their XC skis in molds adjustable along the full length of the ski and the NIS plate is glued to the ski [55]. It is thus presumed the manufacturing itself is sufficiently flexible to cater to specific needs such as positioning of NIS plate and altered camber.

Figure 4.7: Madshus' adjustable ski mold [56].

Chapter 5

Discussion

Design considerations in this project are inclined towards exercise and recreational use. The rules for competitions are rigid and therefore limit the CCSS development to weight reduction and optimizing sitting position, mainly. The sport is relatively young and the equipment is rather simple. The equipment gives the impression of being an adaption of regular XC skiing, this thinking could perhaps be disputed. Focusing on exercise the rules might be disregarded, thus a wider solution space is available. The sport being manifested on all levels, not only among top-athletes, is considered important. Sports equipment encouraging recreational use is therefore fundamental, and might even be a contributing push force in the sport's development.

Key Improvement Points

The work of this project has identified propulsion as the objective with the highest potential of making the sport more attractive and available to a wider user group. The size of the problem to be solved is unclear, though assumed large, at this point. Considerable effort should be employed in exploring various concepts and designs.

Electrical motors on bikes assisting the pedaling have risen in popularity. Motors are widely used in special purpose design bikes, making the sport more accessible to people with various impairments. The implementation of a similar application on a CCSS is not obvious as there is no shaft the assisting motor can be connected to. A motorized attachment could be an option.

The solution should enable gliding in forward direction while maintaining friction backward. In snowmobiles propulsion is solved by the use of tracks, but this causes a lot of friction and obstruct gliding when stopped. A noisy solution or one that damages the ski track might hinder the user's activity as one would not want to cause others inconvenience. Assuming a solution in which the noticeable footprints of tracks could be mitigated, the traction could be positioned in the front, back or middle, and the solution should fit in size. It has been speculated whether the friction with the snow could be tackled with skins arranged in a practical manner.

Now, the assisted propulsion should ideally agree with the user's double poling pace to preserve the nature of the sport. The CCSS development thus far has had its main focus on reducing weight. All extra parts on a CCSS add weight which should be compensated. In other words, double poling dragging along an idle motor and supplements does not solve the problem well. In outdoor sports like XC skiing enjoying the activity in its purity with little aids is a major part of the experience. It is deemed important not to lose the crude feeling of simplicity entirely.

Other objectives such as turning, braking, adjustable seat height and making it easier getting seated are also important, though considered secondary. The primary focus should be set on propulsion as it is the objective most striking while testing commercial CCSSs. A solution for assisted propulsion might incorporate a sensible solution for braking as well.

Prototype Turning

Testing the *4 skis and pivot point* prototype on snow provided useful insight into the aspect of turning. The initial idea was that the CCSSs of today, on 2 long skis, tend to glide straight forward and out of the tracks. To tackle this issue, the long skis were cut in halves and the front pair made able to turn. Simply pushing the prototype, it follows the tracks just as expected. However, with the weight of a person the front pair of skis do not follow the direction change of the curve with the same ease. Much of the user's weight result in high contact forces on the already high friction pivot point. Compared with the two commercial CCSSs, the prototype can handle sharper turns without sliding out of the track, with even better results when the user leans back. The concept is not rejected, as its reluctance to turn is thought to be mended by lower friction in the pivot point and moving it forward. When not in the tracks, the direction of the prototype is hardly controlled. It showed sensitive to transversely inclined trails, minding the test was performed without any path straightening object e.g. a spring.

The prototype glides slightly worse than the commercial CCSSs, though not unexpected as skis are sharply cut and glide is not yet of priority. The prototype is not rigid, and particularly flexible in sideways tilting. Opinions on this feature are divided.

In conversation with the Norwegian national team the issue of pressure point on the skis was discussed. Along with the wish to follow and benefit from the evolution of regular skis, much respect for the camber and positioning of the NIS plate was portrayed. The Norwegian XC ski manufacturer Madshus utilizes a manufacturing process that might possibly be arranged to make modified skis.

Skis providing also an able-bodied with the chance to test gliding was highlighted as an advantage.

A CCSS with 4 short skis disregards the mentioned wishes and points out a different direction. Span curve is an intricate feature that is an object of continuous modification in development. By cutting skis and placing the binding in the middle of the new halved ski, the pressure will not be optimally distributed. However, as practical ski length for the turning prototype is currently unavailable, the camber curve of the cut skis is disregarded in the project. The length of the 4 short skis is shorter than what manufacturers provide. For prototyping this is not an issue, though it might require more effort in convincing the established CCSS environment.

A Moving Sitting Position

The concept of movement in the sitting position is interesting and might be helpful for some aspects of sit-skiing. Athletes with limited muscle function in the back are of special interest. However, some significant limitations are present. Since competition rules of today only allow a rigid CCSS, the concept will not be of interest to competing athletes. The frequency of the DP cycles will vary individually and be adjusted to the speed and terrain. Additionally, a component functioning as a spring will have an eigenfrequency. Hence, dynamics in the sitting position might be difficult to solve ski-technically. The parameters of the ski-technique remain to be clarified. A mechanical solution integrating a variation in frequency might be complex and much uncertainty is present.

If the momentum of the upper body relative to the CCSS is to be utilized regarding propulsion, some leftover energy not used on the DP stroke has to be transformed. Understanding of the unexploited movements is essential, but it is anyway reasonable to assume that the system would experience an energy loss if it should be executed. As of the physical concept of a damper, it results in energy loss when compressed. Thus, its relevance to the concept.

The results of the SkiErgometer test suggest there is no positive effect on the power output having a moving sitting position with a damper. More importantly, a better understanding of a moving sitting position was obtained. The DP technique did not feel effective or natural, the testers expressed. They did not figure out the best way to solve it technically, but the concept was interesting. After compressing the damper by leaning the trunk backward, one had to use either the thigh muscle or force from the DP pull to get up. A force taken from the DP pull will act in the wrong direction decreasing the power from the stroke. The force needed to compress the damper did not contribute positively to the SkiErgometer power output. It was experienced as a disturbance to the DP.

Sources of error in the SkiErgometer test:

- A small sample size, so the experimental output data is not statistically significant.
- Both participants became hungry and tired before the test with no damper.
- The average sitting height was not the same for the two tests. When the seat post was stiff, it was higher, so the participant automatically lent forward and almost lost balance. This may have resulted in less attack in the beginning of the DP cycles.
- For the test with no damper, when the seat post was stiff, there was still some rotation around the joint, so the rig was not completely rigid.
- With a damping effect in the sitting height, the sitting DP was difficult to solve technically. Both participants got some time initially to test and agreed on a specific way to do it, but that might not have been the best way. Individual differences may have appeared.

Hence, the difference in power output will not be interpreted quantitatively, but qualitatively.

Chapter 6

Conclusion

The work of this project is an effort to understand the sport and its users in order to detect the objectives with potential to make exercise with CCSS more attractive.

The exertion in driving oneself and the CCSS forward is identified as the problem which, if solved, would accommodate the most users. The sport would be rewarding not only to the physically strong, and a wider variety of trails could be enjoyed. It would allow longer trips which also top-athletes could benefit from. Whether the assisted propulsion is an effect of a motor or other means should first be decided upon closer consideration and testing.

A CCSS with 4 short skis and the ability to turn has potential that should be further explored. Dynamic seating should only be taken further if it is a sensible secondary feature to the main development in focus.

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Appendix A

Additional Material

Attached is a document of 11 pages by Jon Aalberg describing the proposed courses for the Lillehammer ParaNordic World Cup 2019.

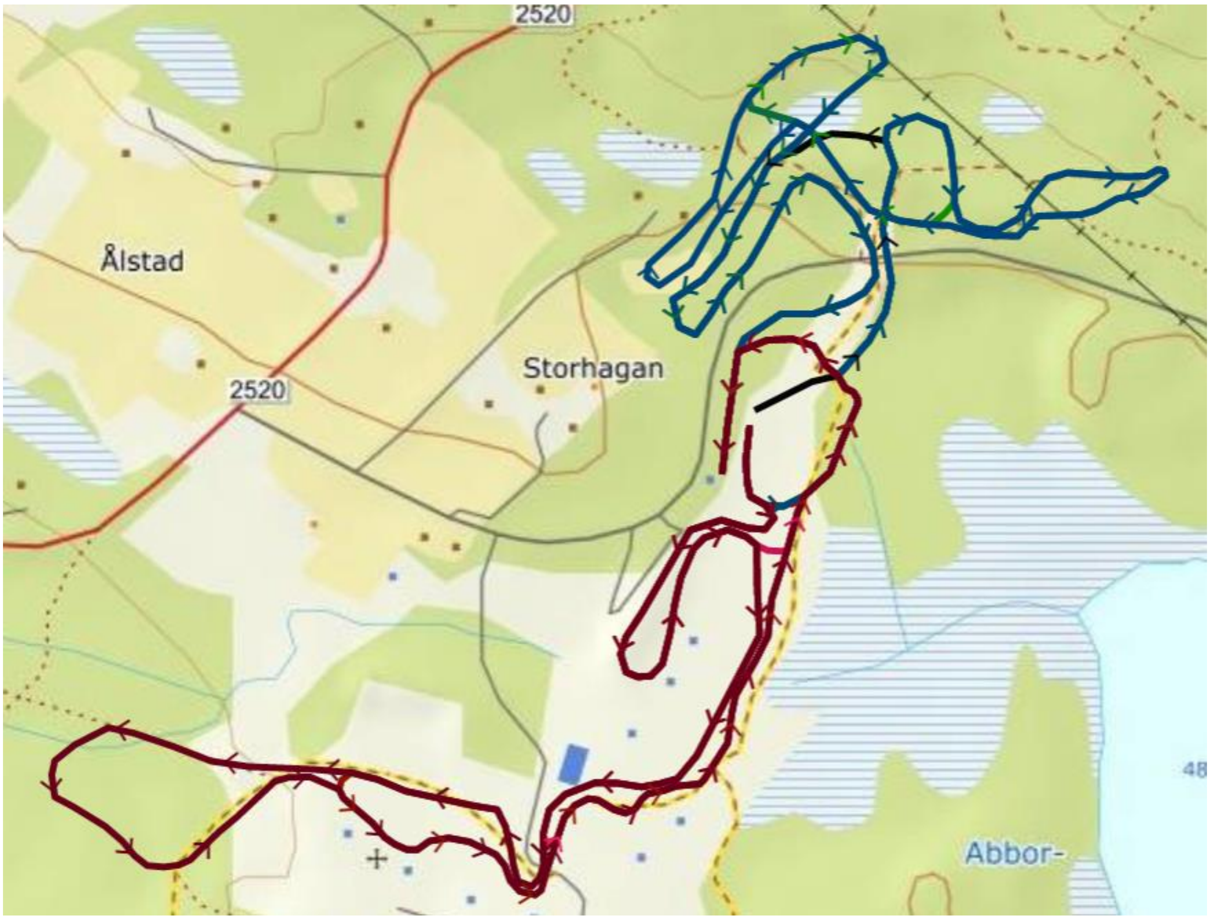
Proposal courses for Lillehammer ParaNordic World Cup 2019

Competition program and courses

Competition	Distance	Course - sitski	Course - standing
CC sprint	sprint	600 – 1000 m	800 – 1600 m
CC short	2.5 km or 5 km	2.5 km	2.5 km
CC middle	5 km, 10 km	2.5 km	2.5 km
CC relay	2.5 km	2.5 km	2.5 km
BT sprint	6 km, 7.5 km	2 km, 2.5 km	2 km, 2.5 km
BT individual	12.5 km, 15 km	2.5 km, 3 km	2.5 km, 3 km

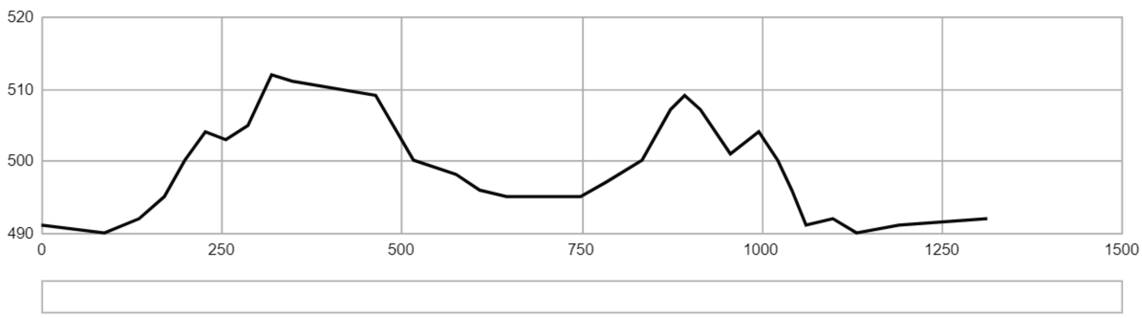
The 2019 courses are divided in an upper- and lower part. The upper part (blue) is for the standing courses and follow much of the FIS World Cup courses. The lower part (red) is used for the sitski courses, and go between the Cross-Country and Biathlon stadium, following mostly the venue's rollerski courses. All courses can, with slight adjustments in the stadium and into the shooting range, be used for both Cross-Country and Biathlon.

The standing courses are all on the upper end of the IPC homologation range, while the sitski courses are on the lower part of the range.



Standing sprint

The start for this course is different than for all other courses (heads out towards the north to create a straighter sprint start). The next page shows an alternative sprint course that follows the "normal" alignment.

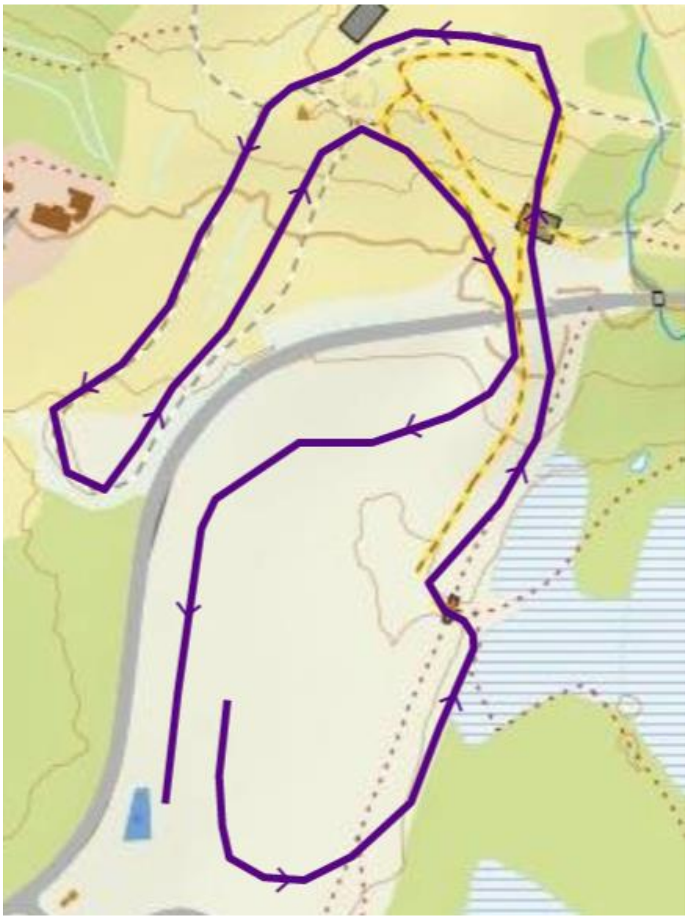


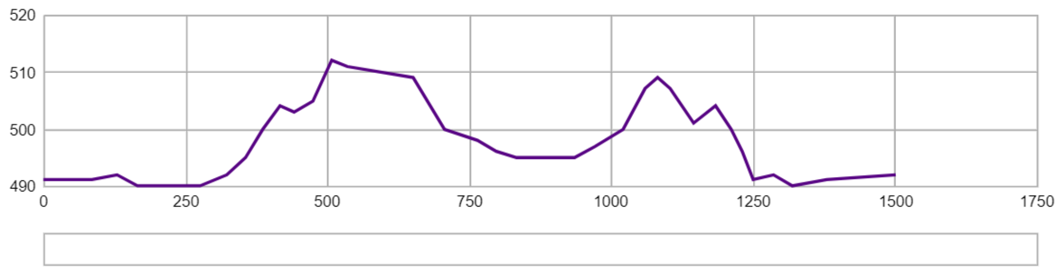
Standing sprint

Course length:	1,314m	Height difference (HD):	22m	Lowest point:	490m
		Maximum climb (MC):	0m	Highest point:	512m
		Total climb (TC):	43m		

EPN

Standing Sprint B

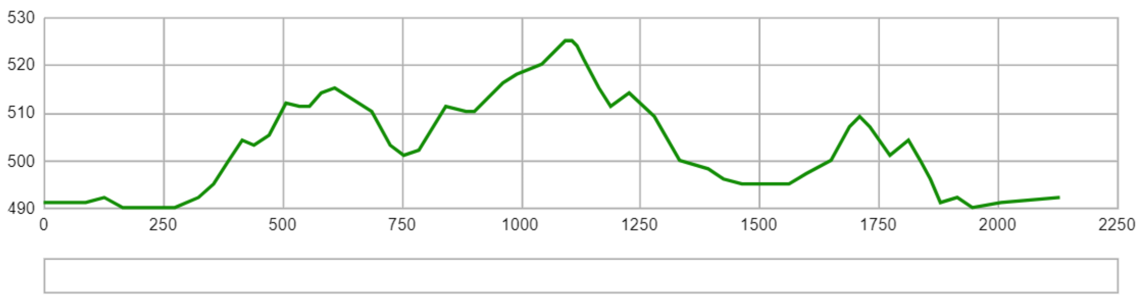




Standing Sprint B

Course length:	1,501m	Height difference (HD):	22m	Lowest point:	490m
		Maximum climb (MC):	0m	Highest point:	512m
		Total climb (TC):	44m		

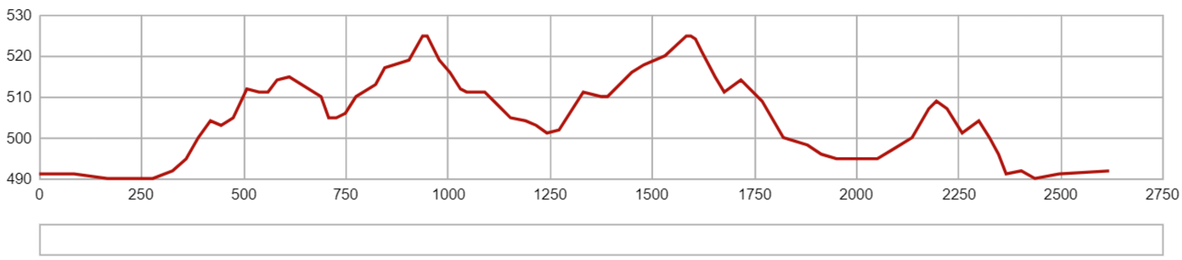
Standing 2 km



Standing 2 km

Course length:	2,130m	Height difference (HD):	35m	Lowest point:	490m
		Maximum climb (MC):	0m	Highest point:	525m
		Total climb (TC):	76m		

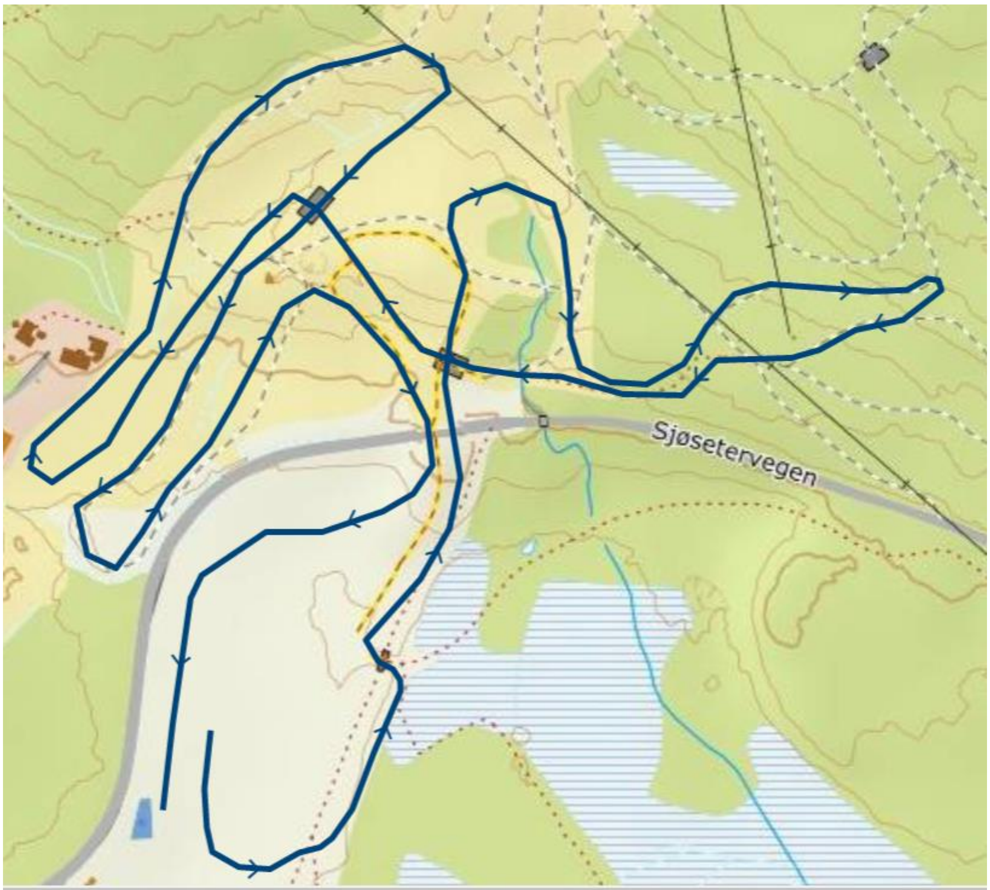
Standing 2.5 km

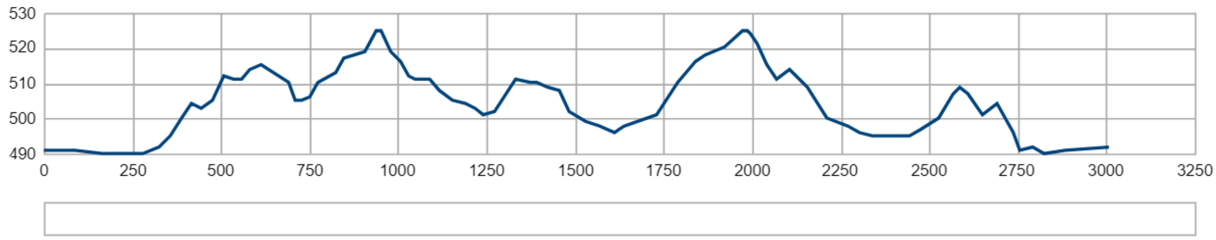


Standing 2.5 km

Course length:	2,618m	Height difference (HD):	35m	Lowest point:	490m
		Maximum climb (MC):	0m	Highest point:	525m
		Total climb (TC):	95m		

Standing 3 km

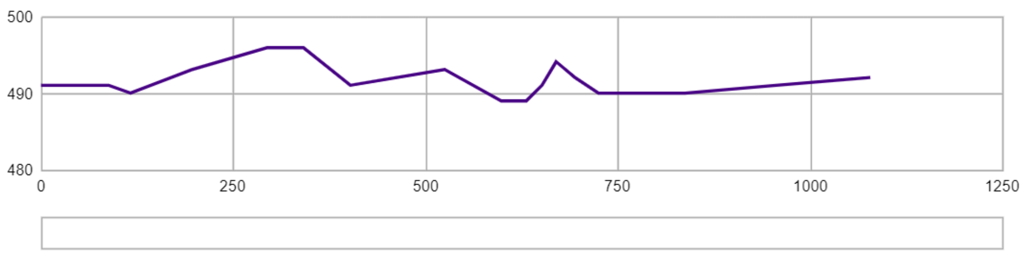




Standing 3 km

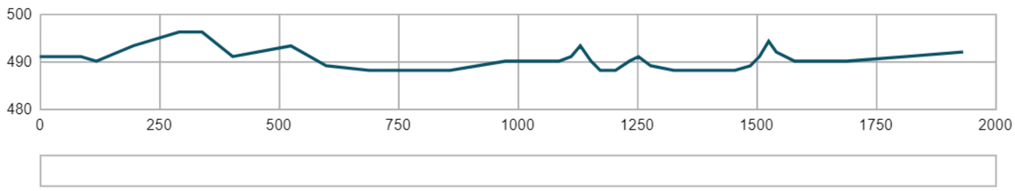
Course length:	3,009m	Height difference (HD):	35m	Lowest point:	490m
		Maximum climb (MC):	0m	Highest point:	525m
		Total climb (TC):	109m		

Sitski sprint



SS sprint					
Course length:	1,079m	Height difference (HD):	7m	Lowest point:	489m
		Maximum climb (MC):	0m	Highest point:	496m
		Total climb (TC):	15m		

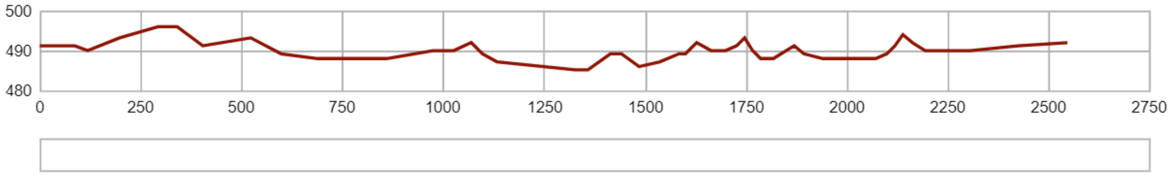
Sitski 2 km



Sit-ski 2 km

Course length:	1,933m	Height difference (HD):	8m	Lowest point:	488m
		Maximum climb (MC):	0m	Highest point:	496m
		Total climb (TC):	24m		

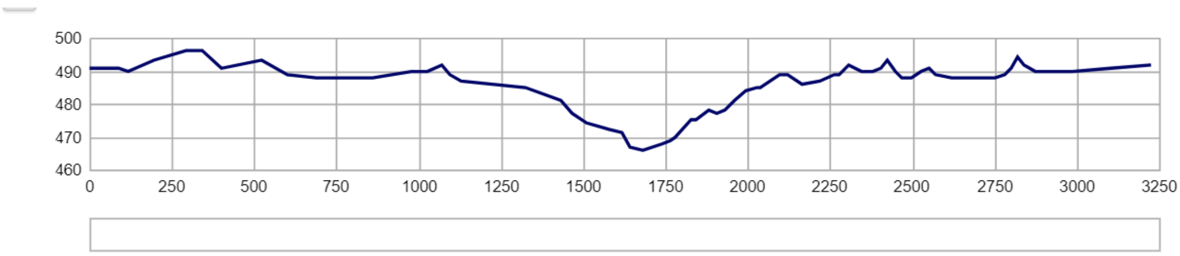
Sitski 2.5 km



SS 2.5 km

Course length:	2,547m	Height difference (HD):	11m	Lowest point:	485m
		Maximum climb (MC):	0m	Highest point:	496m
		Total climb (TC):	36m		

Sitski 3 km

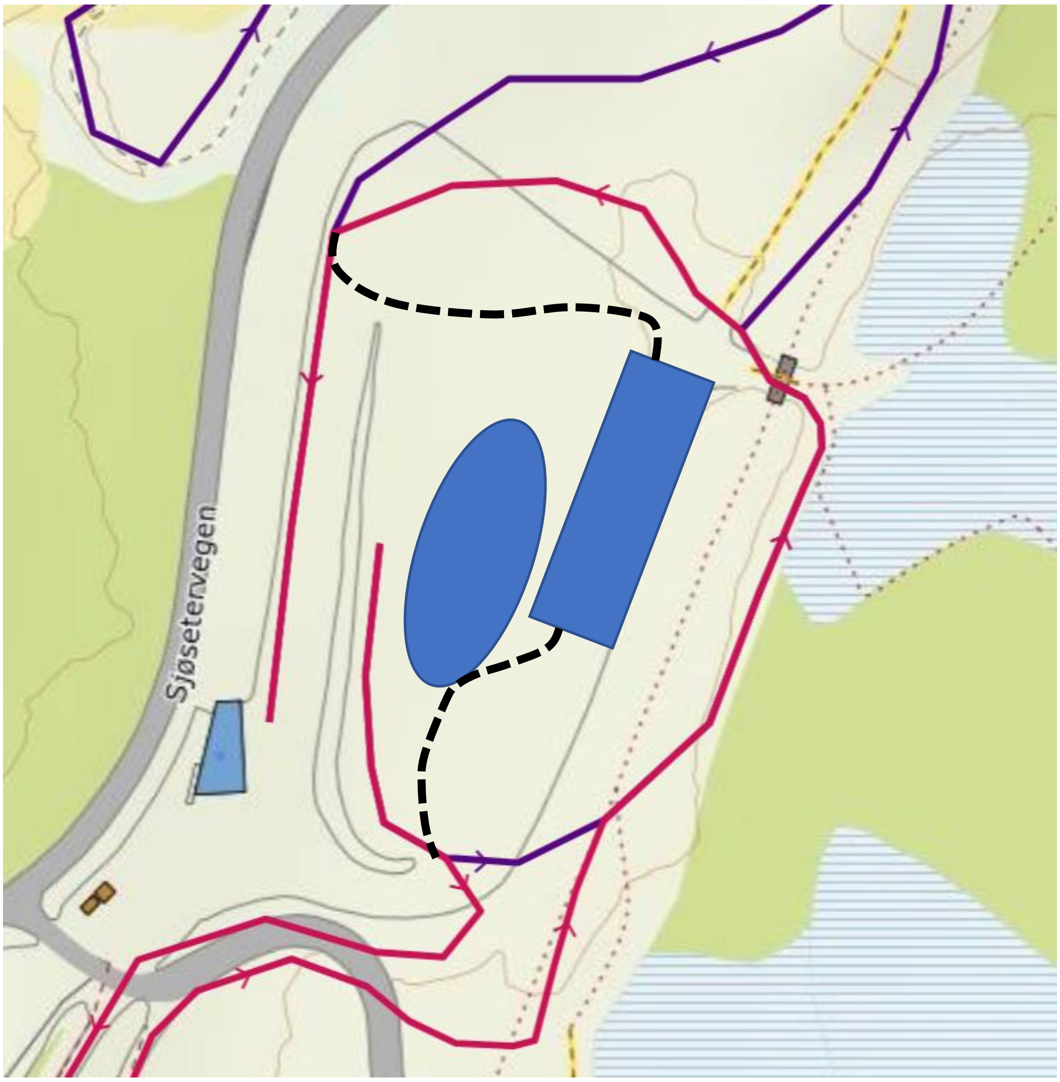


Sit-ski 3.3 km

Course length:	3,227m	Height difference (HD): Maximum climb (MC): Total climb (TC):	30m 0m 56m	Lowest point: Highest point:	466m 496m

Stadium

A stadium with the range and penalty loop are suggested below. This layout should be modified and optimized by the Organizing Committee.



Appendix C

Matlab Scripts

In the appendix is two Matlab codes used to calculate radius, torque and W_d displayed in plots. The first page is a code used to make the graphs shown in figure 5.5 and figure 7.3. Next two pages show the code used to calculate forces and coefficient presented in section 6.1.3 and the plot in figure 6.11.

```
%radiusen
close all, clear all
M=[50; 65; 80; 95]; %kg, totalvekt system, bruker + kjelke inkl. motor og batteri
g= 9.81; %m/s^2,

alfa= [0:25];                          %grader; vinkel motbakke
r= zeros(length(M), length(alfa)); %m, radius drivjul, fra senter til snø
a=alfa*pi/180;                         %rad

T= 45;   %Nm, dreimoment motor
F=T./r;  %N, drive force theoretically
R=0.2;   %m, eksempelradius

for i=1:length(M)                     %for massevektor
    for j=1:length(alfa)              %for helningvektor

       F(i,j) = g*M(i)*sin(a(j)); % + R; total friksjon mot snø + luftmotstand
       r(i,j) = T/F(i,j);             %radius
       t(i,j) = R*F(i,j);             %min. torque
    end
end

figure(1)
plot(alfa,r)
ylabel('Drive wheel radius, r [m]')
xlabel('Slope gradient, alpha [degrees]')
title('Radius < r if acceleration > 0, given Torque 45 Nm')
legend('50 kg','65 kg','80 kg','95 kg')

figure(2)
plot(alfa,t)
ylabel('Motor Torque [Nm]')
xlabel('Slope gradient, alpha [degrees]')
title('Torque needed if acceleration > 0, given r = 0.2 m')
legend('50 kg','65 kg','80 kg','95 kg')
```

```matlab
%piggekjelke skråplan. Utledet fra FLD på øvre ramme.
close all, clear all

M=95; %kg, totalmasse, system, bruker + kjelke inkl. motor og batteri
g= 9.81; %m/s^2,
f = [0.35; 0.4; 0.45; 0.5; 0.55; 0.6; 0.65]; %weight fraction on seat
m=f*M; %vekt på setet

r= zeros(length(f), 5);       %m, radius drivhjul, fra senter til snø
my= zeros(length(f),5)+1;     %friksjonskoeffisient
alfa= [5 10 15 20 25];        %grader; vinkel motbakke
a=alfa*pi/180;                %rad

T= 45; %Nm, dreimoment motor
F=T./r;

%geometri, øvre chassis ABC, stort hjul-prototype:
ACx = 0.845;   %m
ACz = -0.093;  %m, ACz skal være negativ for stort hjul, positiv for minste
ABx = 0.4;     %m
ABz = 0.158;   %m

for i=1:length(f)              %massevektor
    for j=1:length(alfa)      %helningvektor
       F(i,j) = g*M*sin(a(j));   % + R; total motstant, rimpull
       r(i,j) = T/F(i,j);        %radius

      N(i,j)= (F(i,j)*ACz + g*M*f(i)*(cos(a(j))*ABx+sin(a(j))*ABz))./ACx; %W_d
      my(i,j) = F(i,j)/N(i,j); %friksjonskoeffisient
    end
end

figure(1)
plot(N(:,2),my(:,2),'red')
hold on
scatter(N(4,2),my(4,2))

%(
%chassis for lite hjul:
ACx = 0.4;    %m
ACz = 0.052;  %m
ABx = 0.4;    %m
ABz = 0.158;  %m

    for i=1:length(f)
        for j=1:length(alfa)
           F(i,j) = g*M*sin(a(j));
           r(i,j) = T/F(i,j);

          N(i,j)= (F(i,j)*ACz + g*M*f(i)*(cos(a(j))*ABx+sin(a(j))*ABz))./ACx;
          my(i,j) = F(i,j)/N(i,j);
        end
    end

    plot(N(:,2),my(:,2),'black')
    hold on
    scatter(N(4,2),my(4,2))
    legend('Chassis for big wheel','f = 0.5','Chassis for small wheel','f = 0.5')
    xlabel('Normal force on drive wheel, W_{d} [N]')
```

```
    ylabel('Coefficient of traction, \mu_t')
    title('Required traction coefficient as a function of weight fraction on seat and W_{d
}')
%)
fprintf('Med \nTorque på motor           T = %i Nm. \n',T)
fprintf('Total masse på system     m = %i kg. \n\n',M)

fprintf('Helning på bakken på      alpha= %i grader, \n',alfa(2))
fprintf('så krever det en radius på drivhjul\n\n\t\tr < %f m.\n',r(2,2))

fprintf('\nMed vektandel på setet på f= %f, \n',f(4))
fprintf('og et kjelkedesign med pivot point og virkelinje på motor ifht til den på\nACz= %
f m,',ACz)
fprintf('\n\t(skal være negativ når hjulsenter/navmotor er over pivot point på kjelken)\n'
)
fprintf('og ACx = %f, ABx = %f m, ABz = %f m,\n', ACx, ABx, ABz)
fprintf('så samsvarer dette med en normalkraft på hjulet N= %f, \n',N(4,2))
fprintf('og minimum friksjonskoeffisient på\n\t my= %f\nfor at det ikke skal spinne.\n\n '
,my(4,2))
```

```
Med
Torque på motor           T = 45 Nm.
Total masse på system     m = 95 kg.

Helning på bakken på      alpha= 10 grader,
så krever det en radius på drivhjul

                r < 0.278067 m.

Med vektandel på setet på f= 0.500000,
og et kjelkedesign med pivot point og virkelinje på motor ifht til den på
ACz= 0.052000 m,
        (skal være negativ når hjulsenter/navmotor er over pivot point på kjelken)
og ACx = 0.400000, ABx = 0.400000 m, ABz = 0.158000 m,
så samsvarer dette med en normalkraft på hjulet N= 511.895582,
og minimum friksjonskoeffisient på
         my= 0.316141
for at det ikke skal spinne.
```