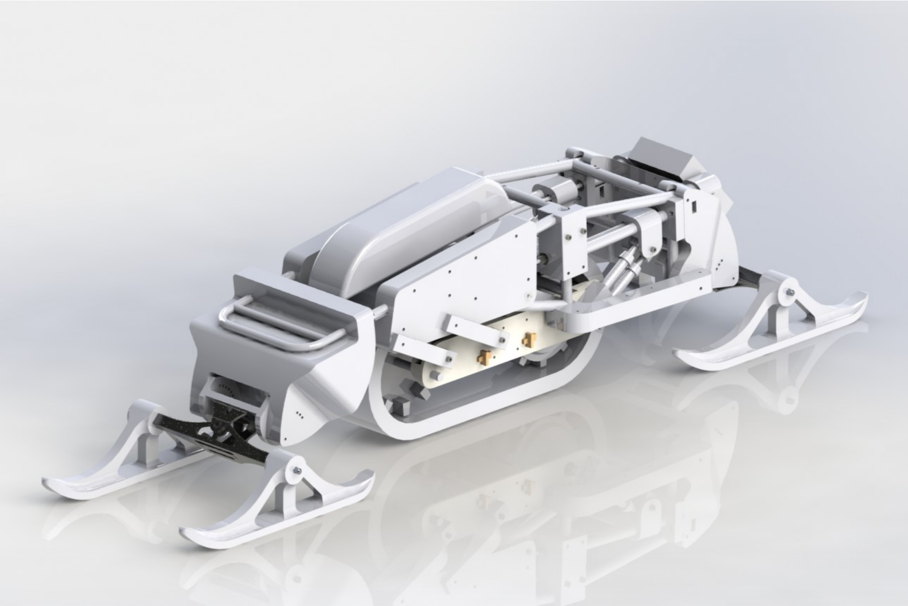
Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

Henrik Krohg Stabell

Development of a cross-country sit-ski prototype with steering capabilities and belt motor for propulsion and braking assistance

Master's thesis in Mechanical Engineering
Supervisor: Knut Einar Aasland
Co-supervisor: Bjørn Åge Berntsen and Sindre Wold Eikevåg
July 2022



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DEPARTMENT OF MECHANICAL AND
INDUSTRIAL ENGINEERING

TMM4960 - ENGINEERING DESIGN AND MATERIALS

MASTER'S THESIS

Author:
Henrik Krohg Stabell

Trondheim, Norway
July, 2022

Preface

This Master's thesis presents the work conducted during the Master's project connected to the course TMM4960 - Engineering Design and Materials, Master's Thesis at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology in spring 2022 and accounts for 30 credits.

The purpose of this project was to develop a cross-country sit-ski prototype with steering capabilities and motor for propulsion and braking assistance. This report presents my work, although some work, such as the interviews and some knowledge gathering in the specialisation project, was conducted in collaboration with Dina Longva Zimmermann.

For this project, motor, battery and motor control from the related projects previously conducted at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology were used. They were sponsored by Elsykkelbutikken Trondheim in 2019. The following material was supplied by Exero Technologies: Four steering trucks, a Spike Snow frame with straps and a seat with a vacuum pillow. The ski wax used on the skis in this project were supplied by Bjørn Åge Berntsen at SIAT.

I would like to show my gratitude to,

Knut Einar Aasland, Supervisor.

Bjørn Åge Berntsen, Co-supervisor.

Sindre Wold Eikevåg, Co-supervisor.

Senter for Idrettsanlegg og teknologi (SIAT).

Mathias Thorkildsen Berg, Exero Technologies.

Stian Kvalvik, Exero Technologies.

Viljar Aasan, Beitostølen Healthsports Center.

Elsykkelbutikken Trondheim.

Hallvard Storli for providing great cross-country ski tracks for testing in Storlidalen in June.

Svein Bergem and Parasport centre in Trondheim for lending an Exero Spike Snow for testing.

Ailin Østerås.

Henrik Krohg Stabell

NTNU, Trondheim 10.07.2022

Abstract

This project aims to develop a cross-country sit-ski prototype with a propulsion assistance and resistance braking motor, as well as steering capabilities and to gain knowledge needed to design and produce a low quantity of units of an improved version. This is for the purpose of improving the quality of life, feeling of independence and training for people with walking disabilities in cross-country skiing, because the solutions and products available on the market today are not sufficient and need improvements.

The cross-country sit-ski is important and valuable for people with walking disabilities and increases their quality of life by allowing them to go skiing and access nature. However, the products available today are suitable for flat ground, but prove demanding and exhausting uphill and can be difficult to steer in turns and brake in downhill. To address this, several prototypes were developed to test concepts and learn about the design possibilities. A final cross-country sit-ski prototype with propulsion, braking and steering capabilities was constructed based on the developed prototypes and the knowledge gained through the development process.

A thorough testing was conducted in cross-country ski trails with three test participants. In the test the cross-country sit-ski was analysed in scenarios such as flat ground, turning, uphill and downhill. Results showed a stable and highly functioning prototype with both propulsion, braking and steering capabilities working. However, adjustments are required for the design to be ready for a low quantity production. Recommendations for further work include and are not limited to; an improved chassis structure, further testing of the steering module and belt traction in more scenarios, faster belt height adjustment and better motor control.

Sammendrag

Dette prosjektet tar sikte på å utvikle en skipiggekjelke-prototype med fremdriftsassistanse- og motstandsbremsings-motor, samt styreegenskaper og å tilegne kunnskap som trengs for å designe og produsere et lite antall enheter av en forbedret versjon. Dette med det formål å bedre livskvalitet, følelse av selvstendighet og trening for personer med ryggmargsskader og gangvansker i langrenn, fordi løsningene og produktene som finnes på markedet i dag ikke er tilstrekkelige og trenger forbedringer.

Skipiggekjelken er viktig og verdifull for mennesker med gangvansker og øker livskvaliteten ved å la dem gå på ski og få tilgang til naturen. Produktene som er tilgjengelige i dag er imidlertid egnet for flatt underlag, men viser seg krevende og utmattende i oppoverbakker og kan være vanskelige å styre i svinger og bremse med i nedoverbakker. For å forsøke å løse dette ble det utviklet flere prototyper for å teste konsepter og lære om designmulighetene. En endelig skipiggekjelke-prototype med fremdrifts-, bremse- og styre-egenskaper ble konstruert basert på de utviklede prototypene og kunnskapen som ble tilegnet gjennom utviklingsprosessen.

Det ble gjennomført en grundig testing i langrennsløyper med tre testdeltakere. I testen ble skipiggekjelke-prototypen analysert i scenarier som flat mark, svinging, oppoverbakke og nedoverbakke. Resultatene viste en stabil og svært fungerende prototype med både fremdrifts-, bremse- og styreegenskaper. Det kreves imidlertid justeringer for at designet skal være klart for å produsere et lite antall av skipiggekjelken. Anbefalinger for videre arbeid inkluderer og er ikke begrenset til; en forbedret chassisstruktur, ytterligere testing av styremodulen og beltetrekk i mer scenarier, raskere beltehøydejustering og bedre motorkontroll.

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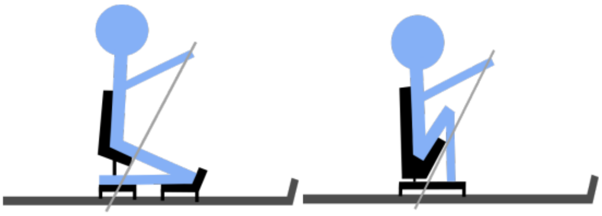
1 Introduction

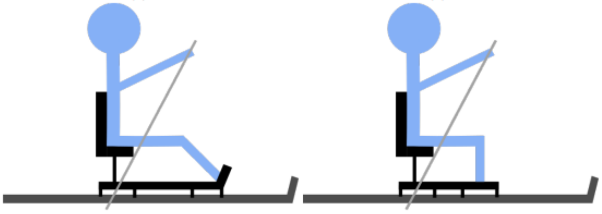
1.1 Background

In recent years, para sports have gained growing attention and the equipment is increasingly being customised to the users, however the available equipment presents limitations and challenges for the users. For people with spinal cord injuries or walking disabilities who cannot go cross-country skiing by standing on their legs, a cross-country sit-ski is used. A cross-country sit-ski (CCSS) consists of a pair of cross-country skis and a seat configuration connected to the skis. Depending on the sitting position, the user sits on the knees or on the but with legs forward. The cross-country sit-skis are great equipment allowing the users to access the ski trails, be active and experience nature. Users of CCSSs include, but are not limited to, people with cerebral palsy, spinal cord injuries and amputees.

There are four main sitting positions used in cross-country sit-skiing; KL, KH, KLS and KN [9] [3]. Figure 2 shows these positions. (a) shows the KL position where the knees are placed lower than the hips and the calves and feet are behind the knees. This position can be used with or without a back support. (b) shows the KH position where the knees are placed higher than the hips and normally includes a back support. (c) shows the position where the knees and legs are straight forward, called KLS position. In this position there is often an angle in the knees. (d) shows position KN, where the user is in a neutral sitting position with knees and hips bent at 90°angles. The position used in a CCSS primarily depends on individual user preferences, but the KL is normally used in competitions to increase performance, and KLS is said to be the most comfortable and best suited for beginners[9][3].



(a) KL (b) KH



(c) KLS (d) KN

Figure 2: The four main sitting positions in cross-country sit-skiing.

Source: [3]

1.2 Problem description

Paralympic cross-country skiing equipment is tailored and centred around the user, however the cross-country sit-skis available today lack proper steering and would benefit from propulsion and braking assistance. The conventional CCSSs available today are suitable for flat ground skiing, but prove demanding and exhausting uphill and can be difficult to steer in turns and brake in downhill. This can result in both dangerous and scary situations for CCSS users and others nearby. In addition, the skiing experience can be reduced if the activity proves too demanding and exhausting. There is therefore a great need for a CCSS with better steering and braking possibilities to increase the safety and comfort of cross-country sit-skiing. Propulsion assistance would also benefit the user experience and improve the quality of skiing for CCSS users.

1.3 Available cross-country sit-skis

There are numerous cross-country sit-ski constructions available to users. These can be divided into two classes, tailored and untailored. Tailored cross-country sit-skis are bespoke and are made to fit only the one person it was made for. This is typically the case for athlete CCSSs used in competitions. Untailored CCSSs are not customised to fit only one person, but designed to fit a general user group. These types are often designed with seats and supports to be adjustable to fit individual user preferences. Some commonly used non-tailored CCSSs are presented below, in addition to one ski aid equipment construction worth mentioning because of its configuration with four skis.

Skeno Power

Skeno Power is a CCSS developed by Norwegian based Skeno AS [21]. Figure 3 shows the CCSS. It is designed to be used with sitting position KL and can be modified to accommodate individual user needs, especially for amputees. The CCSS has several straps to fasten the user and a brake lever positioned at the front between the knee supports. Users can choose whether to mount the structure on cross-country skis or on a wheel based platform. The chassis is mostly aluminium, while the supports are made out of composite materials.

Figure 3: Skeno Power cross-country sit-ski.

Source: [21]

Exero Spike Snow

Exero Spike Snow is a CCSS developed by the Norwegian company Exero Technologies [28]. It is a light aluminium structure designed for position KLS, but does not have a back support. The seat angle can be adjusted to accommodate individual users' preferences. Three straps are used to fasten the user. The Exero Spike Snow is shown in Figure 4.

Figure 4: Exero Spike Snow cross-country sit-ski.

Source: [28]

Tessier Eskaip

Tessier Eskaip is a light and highly customizable cross-country sit-ski made by the french company Tessier [29]. The aluminium frame is fully adjustable, enabling individual settings for seat height, seat angle, footrest and centre of gravity. The CCSS can also be used with a back support and accommodates KH, KN and KLS positions. Optional brake levers on the side provide some speed control downhill. Several seats are compatible and a plate located at the rear allows for push assistance by a fellow skier if needed. Two to three straps securely fasten the user. With brakes, the frame weighs 4.9 kg. The Eskaip is shown without back support in Figure 5.

Figure 5: Tessier Eskaip cross-country sit-ski.

Source: [22]

HandiSnow-4

Handisnow-4 is a lightweight aluminium CCSS made for double poling in position KLS on snow, ice and hard surfaces. It is produced by a Norwegian company and comes in 4 sizes and has a back support. Additional equipment that can be mounted on the CCSS for extra aid include: companion bar, support ski, headrest, neoprene vest, folding draw bar with harness and elastic ropes with harness. The largest version allows for a leg length of 75-107 cm, has a sitting height of 27 cm, width of 40 cm and weighs 6.3 kg. Figure 6 shows a picture of HandiSnow-4. [10]

Figure 6: HandiSnow-4 cross-country sit-ski.

Source: [10]

HandiSnow-5

HandiSnow-5 is a CCSS for use with the KL sitting position. It is produced by a Norwegian company in light aluminium and weighs 7 kg. The seat and knee supports can be angled to adjust for a more comfortable sitting position. It also has a brake handle between the skis and comes in two sizes. The largest version has a seat width of 35 cm and front and rear seat height of about 43-46 cm and 47,5-50 cm respectively. The CCSS is shown in Figure 7. [11]

Figure 7: HandiSnow-5 cross-country sit-ski.

Source: [11]

BeitoSkilator

The BeitoSkilator is a construction to aid disabled people in skiing. It is not strictly a CCSS, but is used to help people ski. The construction is presented in Figure 8. It is used for standing skiing, where the user can hold in the handles (black) for support. There is also a seat at the back. The construction has four skis to provide good stability. The rear skis provide sideways stability and the front skis are placed closer, allowing them to fit inside classic ski tracks and guide the user in the classic ski tracks. The construction comes in two sizes, junior and adult, and can be disassembled in two pieces for easy transport. The adult version is 200 cm long without skis, 69 cm wide, 93 cm high and weighs 12.5 kg. [5]

Figure 8: The BeitoSkilator.

Source: [5]

1.4 Previous work

Paralympic cross-country skiing is a field with limited research and few academic publications are available, however important research has been conducted locally at the Norwegian University of Science and Technology. In the spring of 2018 a master's thesis was conducted where a prototype of a cross-country sit-ski on wheels with steering abilities was developed. This prototype would later be further developed into what is now the Exero Spike [27]. Through the research and development, a lot of knowledge about steering possibilities and sitting positions was gained. Additive manufacturing was utilised extensively to build prototypes. For the steering module on the prototype, channel trucks similar to that on the Exero Spike were used. [6]

In the spring of 2021 a CCSS prototype with propulsion and braking capabilities was developed as part of a master's thesis. The developed cross-country sit-ski was designed for a KL sitting position with adjustable seat height and seat angle. A belt track was integrated inside the aluminium frame to provide propulsion assistance. An electrical bicycle hub motor of 250 watts was used for propulsion, supplied by a battery placed in a backpack worn by the user. The motor was controlled by using a motor control unit with a thumb throttle connected to a ski pole. Through tests, the cross-country sit-ski performed well and provided great additional propulsion, especially uphill. An additional and unanticipated finding was that the belt track also provided controlled braking downhill. However, the CCSS did neither provide controlled steering, nor accommodate other sitting positions than KL. The master's thesis was a continuation of a master's thesis project on the same topic conducted in spring 2020. Figure 9 shows the developed prototype and the main components. To the author's knowledge, no other cross-country sit-skis with propulsion and braking assistance has been developed. [3]

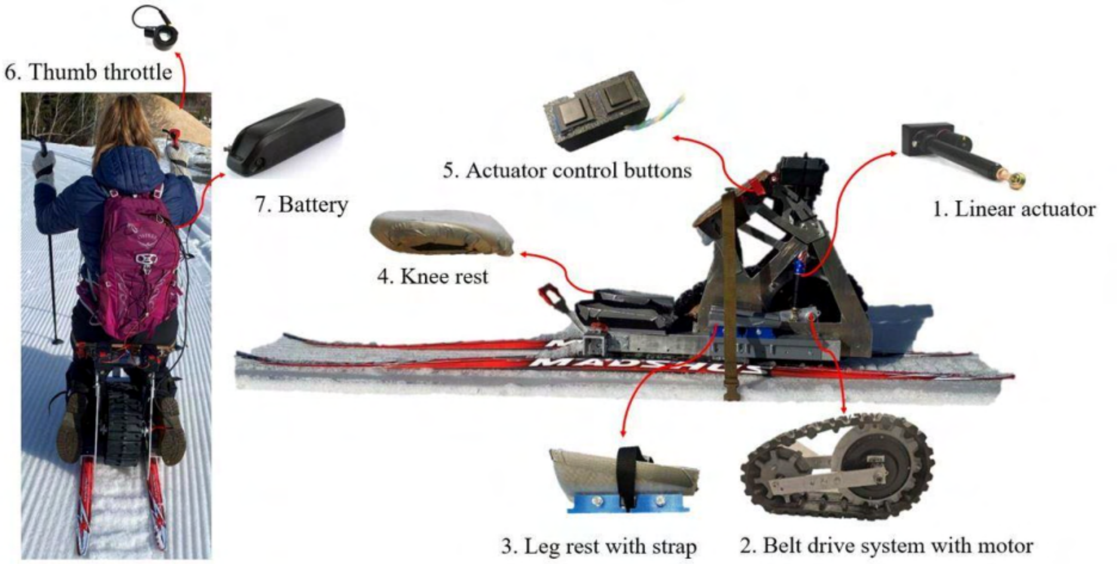


Figure 9: Prototype developed through previous research at NTNU spring 2021.

Source: [3]

In autumn 2021, a specialisation project connected to this master's thesis was conducted. Through the project, Henrik Krohg Stabell explored several concepts and prototypes, gained a lot of knowledge and eventually constructed a CCSS prototype with steering and propulsion assistance. The final prototype was tested and valuable findings were made. Overall, the work and findings from the specialisation project were of great importance to this master's thesis project. One of the most important findings was that the steering mechanism and the motor proved to work well. The suspension and height adjustment mechanism also showed promising results from testing, although significant alterations would be necessary to perform as intended in a final product. For this reason, important and relevant work from the specialisation project will be presented in this thesis. The full specialisation project report can be found in Appendix C. [23]

1.5 Project scope

The main objective of this project is to develop a cross-country sit-ski prototype with steering capabilities and suspended motor-driven belt track for propulsion and braking assistance. The CCSS should meet necessary user needs, be designed to accommodate a diversity of users and incorporate a proper sitting position enabling double poling. The overall vision of this project is to make cross-country skiing accessible for everyone.

The objectives of this master's thesis can be broken down into the following bullet points:

- Gather knowledge to understand the sport of cross-country sit-skiing.
- Develop designs to enable steering.
- Develop designs to enable controlled propulsion and braking with a motor-driven belt track.
- Construct a test rig to develop, test and find the best solutions for steering, suspension and height adjustment mechanisms.
- Design and construct a CCSS frame and integrate the most suitable suspension and height adjustment mechanism.
- Design and construct parts to be integrated on the existing Exero Spike Snow frame to enable steering, belt track drive with suspension and regulation of belt track height.
- Test the constructed prototype and document findings.

Furthermore, relevant laws and regulations should be followed. The developed CCSS should therefore not have an auxiliary engine with greater nominal effect than 250 W and should have a mechanism preventing the contraption from reaching greater speeds than 25 km/h with engine power. At greater speeds, the motor should not provide propulsion assistance. In addition, for start-up assistance the motor alone is allowed to provide propulsion of up to 6 km/h. [17] [19] [24]

1.6 Thesis structure

This paper is divided into ten sections: Introduction, Development approach and methodology, Preliminary work in the specialisation project, Design and construction of test rig, Design and construction of parts and mechanisms to integrate motor and turning on the Exero Spike Snow, Prototype testing and results from testing, Discussion, Further work, Conclusion and Appendix. In the **Development approach and methodology** section the development approach and methodology applied in the project is explained. First, the need-finding process is explained, then theoretical concepts development and prototyping are described before finally prototype testing is clarified. Later, in the **Preliminary work in the specialisation project** section the prototypes created throughout the specialisation project are presented, their value generation specified and the findings from testing of the developed final prototype emphasised. The **Design and construction of test rig** section describes the design and construction of a test rig intended for testing and development of the best suitable suspension and steering components for a CCSS. Afterwards, in the **Design and construction of parts and mechanisms to integrate motor and turning on the Exero Spike Snow** the design and construction of parts to enable propulsion and steering on the existing Exero Spike Snow is detailed. In the **Prototype testing and results from testing** section the final testing and qualitative and quantitative results are presented. The results, initial objectives and achievements are discussed in the **Discussion**. Recommendations for future work are presented in the **Further work** section before the **Conclusion** at the end of the thesis. The **Appendix** contains a **Circuit diagram** of the electronics used for the height adjustment mechanism and the affiliated **Arduino code** as well as the **specialisation report** conducted in autumn 2021.

2 Development approach and methodology

The development approach chosen for this project was a combination between set-based concurrent engineering [16] [32] and the hunter-gather wayfaring approach used specifically in fuzzy front end projects [25]. Overall, both the specialisation project and the master's thesis project were divided into four stages completed in chronological order: Knowledge gathering and learning process, Theoretical concepts and sketching, Prototyping and model building, and finally, Prototype testing in the specialisation project. The specialisation project conducted during the autumn of 2022 provided extended knowledge, and was a central part of the learning process. This project also constitutes a larger part compared to the master's project during spring 2022. The start of the master's project focused mainly on the development of prototypes and models to reach the objectives, Section 1.5, as most of the learning process had been implemented in the specialisation project. In the Knowledge gathering and learning process stage, the focus was to gather as much knowledge about the field of cross-country Paralympics and cross-country sit-skis and find information from relevant previous work. Then, in the Theoretical concepts and sketching stage, theoretical concepts were developed and sketches of the most viable concepts were made. This was followed by the Prototyping and model building stage where prototypes and models were constructed and tested to enable a constant learning process during the development. Eventually, a final prototype was more thoroughly tested to learn what worked with the developed concept and find points of improvement. Even though the projects primarily followed these four stages in chronological order, work was done in all four concurrently and in smaller sets and iterations as proposed in product development literature [32] [25] [7] [16]. As the projects developed, new knowledge was found and new designs were proposed, requiring further knowledge gathering and testing which in turn resulted in new design specifications and alterations.

2.1 Knowledge gathering, interviews, learning process and needfinding

The knowledge gathering and learning process stage was the initial phase of the projects, where the overall objective was to explore and gather knowledge relevant for the project. This included knowledge about the concept of Paralympic skiing, need-finding, the generation of as much insight into cross-country sit-skis, issues with available equipment and the development of a view from the perspective of the user of such equipment. Through a meeting with representatives from Exero and Beitostølen Health Sport Centre Norway, valuable insight into Paralympic equipment was gained. The most important was that even though the KL sitting position will be most performance enhancing for users, KLS is usually more comfortable, less straining on the knees and better for longer trips. In addition, previously conducted research relevant to the project was explored and interviews with CCSS users were conducted.

Moreover, exploration into previous relevant research and testing of both the CCSS prototype developed at NTNU in spring 2021, shown in Figure 10 [3] and the Exero Spike, Figure 11 [27], set the fixed points in terms of design choices for these projects. The previous research product development of the Exero Spike gave valuable insight into possible steering mechanisms using trucks [6]. Based on tests and evaluation of the motorised CCSS prototype developed in spring 2021 and the affiliated findings [3], a belt driven electric motor system was chosen as the propulsion and braking assistance because of its superior performance. Furthermore, a suspension system would be explored to ensure better belt traction, as the belt drive on the CCSS developed in spring 2021 lacked suspension which resulted in lost traction [3]. The seat and sitting position from the prototype were used as reference for a possible knee sitting CCSS, although the overall desire was to develop a CCSS where all the four sitting positions introduced earlier could be integrated and used. Later in the development, the KL sitting position was abandoned in favour of the KLS position because it seemed to better suit longer trips and new users and its higher reported comfort. Based on the positive experience from the Exero Spike, a similar turning mechanism would be preferred if possible. This would allow for turning, but would also require four independent skis.

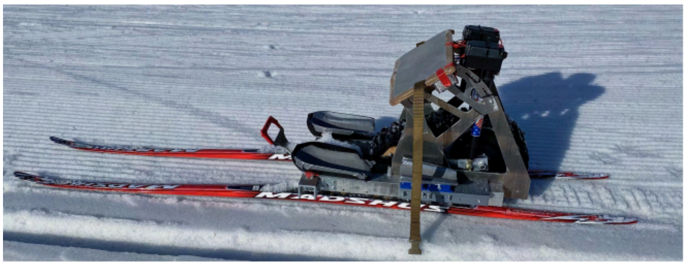


Figure 10: Prototype developed at NTNU in spring 2021.

Source: [3]

Figure 11: Exero Spike.

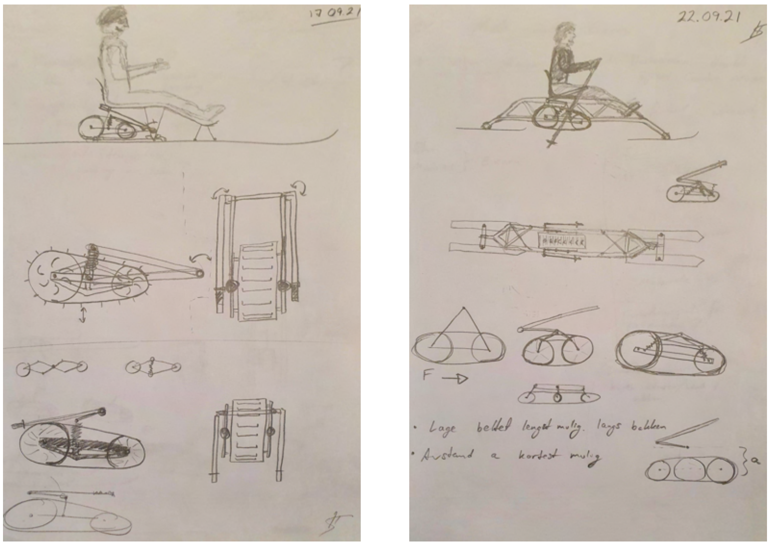
Source: [27]

Furthermore, interviews with two users of cross-country sit-skis were conducted to increase the insight into aspects of cross-country sit-skiing, as well as the problems associated with the use of such equipment. The interviewed users were both frequent users of cross-country sit-skis. One of them had a high spinal cord injury, the other had cerebral palsy (CP). Through the interviews the users stressed the importance of stability and issues with steering. Steering and braking was normally controlled using the ski poles. Uphills were described as exhausting if they were more than 2 metres in elevation. This problem was usually solved by avoiding steep hills or with pulling or pushing help up the slope by another skier. Additionally, the interviewed users stressed the importance of a good and comfortable sitting position and other less obvious issues such as reduced gripping force for people with CP and different requirements depending on the height of the spinal cord injury. The most comfortable sitting position was said to be the sitting position KLS, with feet forward. When presented with the idea of a motorised belt driven CCSS, they were very positive and welcomed the concept. However, two important concerns were pointed out: the possible destruction of ski trails by the belt and that the CCSS should be constructed to be convenient and easy to handle for the user.

To summarise, through this initial need-finding and knowledge gathering phase the following challenges were discovered: Arm and gripping strength, sitting position, steering, braking, convenience and user friendliness, fit in the classic ski tracks and balance. Through this phase in the project the following fixed design points were decided on: A motor driven belt system, steering capabilities and a suspension module to control for uneven terrain. A motor driven belt system was chosen because of the promising results from previous development [3]. Suspension was decided because the same previous development lacked spring suspension, which resulted in reduced traction [3]. The sitting position was not decided on, although a KLS position was desirable for comfort. These were the initial “set needs” for the prototype to be developed. However, if new knowledge gained later in the project would deem it necessary, these fixed points could be altered to construct a more suitable end prototype.

2.2 Theoretical concepts and sketching

In the early stages of the projects, theoretical concepts to accommodate the user needs were developed and sketches were created to visualise the variety of possibilities. These theoretical concepts and sketches were constructed in conjunction with the need-finding stage. Figure 12 shows two sketches of the many concepts that were developed. The sketch in Figure 12a shows a CCSS with one pair of skis, a belt drive system with suspension and height adjustment and a user in sitting position KLS. Figure 12b shows a CCSS with two pairs of skis, a truss structure chassis, a belt drive system with suspension and height adjustment and a user in sitting position KLS. The height adjustment of both concepts were designed to be operated using a lever arm. By incorporating a height adjustment mechanism for the motor and belt, the issues with traction and height differences in the classic ski track could potentially be accommodated [3]. The two sketches show the lever arm in opposite directions and with slight variations in lengths and positions of members. From chosen concepts and sketches, 3 dimensional prototypes were created, both physical and analytical, to further investigate, learn and iterate to final working prototypes.



(a) Sketch 1, one pair of skis.

(b) Sketch 2, two pairs of skis.

Figure 12: Examples of early stage sketches of concepts for a cross-country sit-ski with motor.

2.3 Prototype and model building to fill knowledge gaps

In the prototyping stage, concepts were further developed and investigated in 3 dimensions, primarily physical models, to give answers to design questions. Prototyping was used to answer questions about design, to learn what worked and how it worked and to gain relevant knowledge as time and cost effectively as possible. By developing prototypes, cost and risk were also reduced and most importantly, the possibility to discover and explore opportunities was increased [25]. These are some of the most important properties of prototypes [20] [12]. In the prototyping process, there was also a hope of detecting unanticipated phenomena and discovering unknown unknowns [26] [13], but this would also be possible to discover in the user testing phase or through experience prototyping [8].

Throughout the project, prototypes of varying form and function were developed. The prototypes ranged from focused to comprehensive [32] and from low to high fidelity and resolution [12] depending on what they were trying to answer or gain knowledge about. Initially, physical prototypes of low fidelity and low resolution were developed. These included Lego and paper models. Both looks-like [32] prototypes, such as the early paper models, and work-like [32], such as the suspension module, were utilised. Parts and modules were mostly focused to see if the individual sections functioned as intended before the most optimal were integrated into the final prototype. The final prototypes ended up being the most comprehensive and with the highest fidelity.

2.4 Prototype building in the master's thesis project

With the knowledge and findings from the specialisation project, a new test rig was designed to test and further develop a well functioning motor and suspension system. In addition, tests would be conducted to investigate the influence of different angles of the turning mechanism at the front and rear of the CCSS test rig. The plan was to use a test rig to develop a well functioning motor and suspension module, and then, based on the findings through testing, construct a light and rigid chassis that would accommodate a good and comfortable sitting position. The chassis was proposed to be constructed of either 3D-printed sections, welded aluminium, laser cut plates of aluminium, composite shell or a combination of several of the mentioned. The development of the test rig is further explained in Section 4.

A little while into the construction of the test rig the design and development was halted. Instead the focus turned to the existing Exero Spike Snow. A decision to try to add steering mechanisms and integrate a motor with suspension on the Spike Snow was made. Due to the design restrictions and design challenges of integrating this, mostly because of limited space and already existing chassis geometry and dimensions, the design possibilities were restricted. For example, previously thought out designs for the suspension module were not feasible due to the limited space. Using the existing Exero Spike Snow frame also meant that a sitting position allowing for a larger degree in the hip and lower feet would not be possible, as was the original plan. The development of parts to integrate steering and propulsion on the Exero Spike Snow is covered in Section 5.

2.5 Prototype testing

Prototypes were continuously tested in the workshop for their function as quickly as possible to learn as fast as possible, and thereby iterate as fast as possible. The hunter-gather way-fairing approach [25] was applied to a great extent, resulting in the design and prototype building and prototype testing phase being conducted concurrently. The final prototypes were more thoroughly tested in cross-country ski trails. The wood prototype developed in the end of the specialisation project was tested at Granåsen in Trondheim and the final prototype eventually developed in the master's project was tested at Storlidalen near Oppdal, Norway. Through the testing, valuable insight into successful aspects of the design and possible improvements were confirmed or revealed. The testing and results of the prototype developed during this master's project are covered in Section 6.

3 Preliminary work in the specialisation project

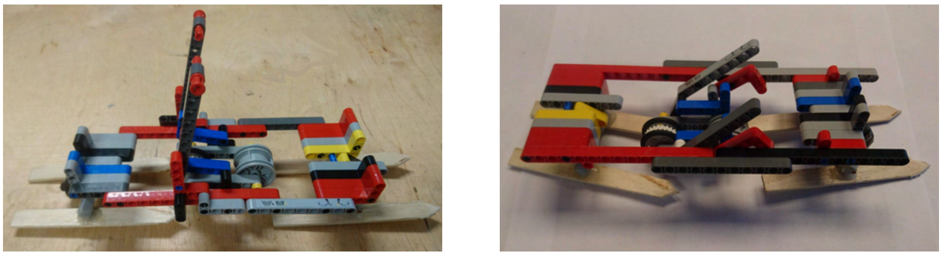
This section covers the work conducted during the specialisation project autumn 2021. In this stage of the project most of the idea generation, concept generation, knowledge gathering, need-finding and prototype building were conducted. More specifically, this section covers the prototype development, testing of prototypes and findings from the specialisation project.

3.1 Prototype development

In the prototyping phase of the specialisation project, simple low resolution models were initially constructed, followed by more refined and focused prototypes. In the end, a final prototype was developed based on the most optimal prototypes of each module. First, low resolution models in Lego and paper were constructed, primarily to test out concepts and theoretical ideas and to learn about the design domain. This was followed by mostly full size models and prototypes of specific modules, such as the suspension module and the height adjustment module. These ranged from focused to comprehensive prototypes, with increasing fidelity.

3.1.1 Concept modelling with Lego

Lego modelling was utilised at an early stage in the project to further develop the theoretical concepts. Primarily the two functions of steering and suspension with height adjustment were investigated with the prototypes. Figure 13a shows a Lego model with four skis and a height adjustment lever mechanism. In this model the motor section (grey wheels) was only connected to the lever arm mechanism through two connection points. This created a pivot point intended to simplify the construction. Concerns about the possible uneven pressure distribution from the belt to the ground because of this pivot point connection resulted in a second Lego model to solve this possible issue. Figure 13b shows the second Lego model with turning skis and a modified connection between the lever arm and the motor module. The four connection points linked the two modules together, hindering the pivot of the motor module. The height adjustment mechanism proved promising. Both models were constructed with the same steering mechanism. By tilting the chassis, the skis turned in the same way a skateboard turns [6]. The mechanism for steering was tested and proved promising.



(a) Lego model 1.

(b) Lego model 2.

Figure 13: Examples of early stage Lego model prototypes.

3.1.2 Small size paper model of concept

A small size paper model was constructed concurrently with the Lego prototypes to increase the prototype fidelity and resolution. The first version was roughly 400mm long. A second and shorter version shown in Figure 14 was roughly 300mm long and consisted of a paper chassis, four skis, a height adjustment mechanism and a seat. Unlike the Lego prototypes, this model did not incorporate a functioning turning mechanism. However, the pivot point issue with the height adjustment mechanism was discovered with this paper model. When the force from the belt was transferred to the ground through propulsion or braking, the momentum created through the point connecting the motor module and height adjustment module would result in a pivot. This pivot resulted in an uneven pressure distribution between the motor module and the ground. The second Lego model incorporated a modified connection to accommodate this issue. The small size paper model proved important in visualising the concept of four skis for turning, the height adjustment mechanism, chassis construction and sitting position.

Figure 14: Small size paper model with chassis, four skis, height adjustment mechanism and seat.

3.1.3 Full size paper model of chassis

To learn more about the construction of the chassis and the general design domain, a full size paper model was created. This prototype gave insight into the size of the chassis and the possibilities of where to place the seat and general sitting position as well as the space available for the motor and height adjustment module. Figure 15 shows a sketch of the proposed chassis with dimensions to accommodate the size of a motor module and skis. At this stage skis of 87cm were found to be the shortest mass-produced skis [14] and the chassis was designed with this in mind. Because of the increased wear on skis used on CCSSs, these skis could be changed when worn out or damaged and were thought to be most fitting. However, later on in the project additive manufactured skis which were only 30 to 40 cm long were used instead. Additive manufactured skis allow for shorter skis and better customizability in the development process.

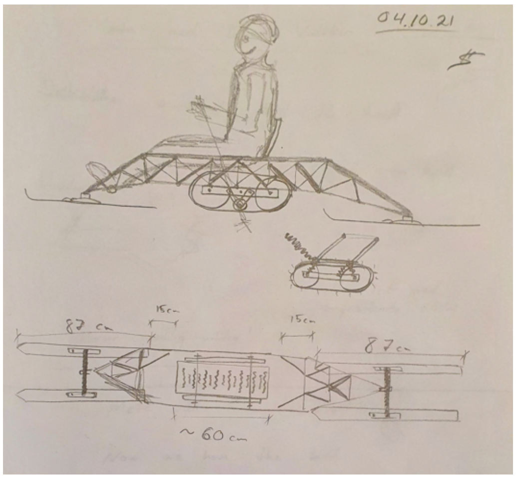


Figure 15: Sketch of full size paper model with important dimensions in cm.

The full size paper model, shown in Figure 16, was constructed as a truss structure using rolled A4 paper and tape. The design was inspired by truss bridges, but on this model the chassis ended in single points on each end. This was to accommodate steering possibilities. The first version of the chassis had longer "legs" and a wider span from the front support point to the rear support point. To test the sitting position and get a feel for the size and form of the chassis, a chair was used to sit on. The chair was placed beside and inside the paper model, giving feedback about the sitting position without constructing a rigid chassis in, for instance, steel. This saved a lot of time and resources, while still providing necessary new knowledge about the design. The design and dimensions of the chassis proved promising and a wood chassis was therefore constructed.

Figure 16: Full size paper model of chassis with user sitting on chair behind to test sitting position and general form.

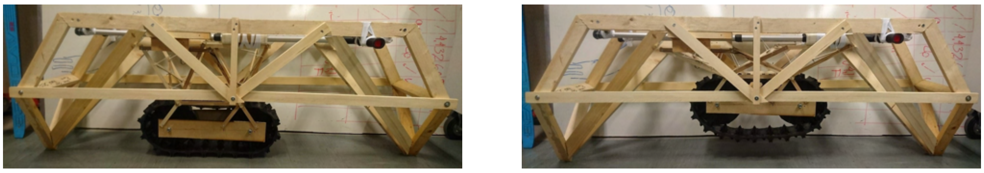
3.1.4 Wood model of chassis

Using the dimensions and knowledge gained from assembling the full size paper model, a wood chassis was constructed. The wood prototype was roughly the same length, width and height as the paper model. To save construction time and material and better accommodate anticipated forces, the truss structure was altered slightly. Figure 17 shows the wood model of the chassis constructed with wood and screws. Inside the chassis an early version of the suspension module with belt and wheels can be seen. This wood chassis would later be used to mount and integrate the different modules of the CCSS. The frame strength was tested by sitting on it and applying loads from the top at different angles to verify that it would be strong enough to be used as a test chassis in further testing.

Figure 17: Full size wood chassis frame prototype.

3.1.5 Suspension mock-up with belt and wheels

A simple suspension prototype was constructed based on the theoretical concepts and the knowledge gained from the early prototype building. Much inspiration was taken from snowmobile track suspension, ATV add-on tracks, aeroplane landing gear, collapsible ambulance stretchers and mountain bike suspension mechanisms. Figure 18 shows the initial suspension mock-up module integrated on the chassis. It consisted of two plates connecting the two axles holding the wheels in place. The wheels and belt track were from a snowblower. Six short members, resembling springs, connected the plates to two horizontal members. These horizontal members were connected to a suspension frame structure allowing for height adjustments. This is further discussed in Section 3.1.8. The mock-up suspension prototype worked as proof of concept and produced valuable knowledge about the design. Firstly, issues with the stability of the motor module were discovered. The current connection with the short members would create an instability where the motor module would be able to twist or lean to one side. Secondly, this suspension module could be further improved to allow for better movement and surface contact over uneven ground, especially when leaning the chassis when turning. Lastly, the importance of belt tension was highlighted. These issues were largely solved with the next version prototype discussed in Section 3.1.6.



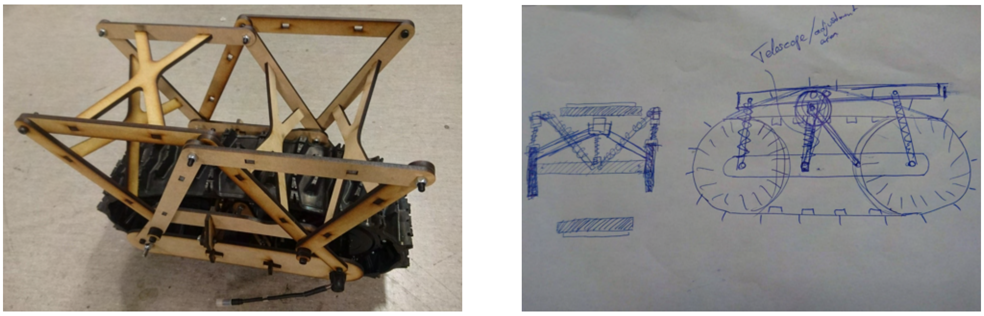
(a) Suspension mock-up module in lowest position.

(b) Suspension mock-up module in high position.

Figure 18: The suspension mock-up module with belt and wheels mounted on the wood chassis.

3.1.6 Suspension prototype in laser-cut MDF

Based on the first suspension prototype, a second version was constructed in primarily medium-density fiberboard (MDF). The design was first sketched and modelled using computer-aided design (CAD) and then laser-cut in MDF and assembled with an electric motor inside and a belt tension wheel. Figure 19a shows the prototype of the suspension module. Figure 19b shows a sketch of the suspension with structural members and belt tension mechanism visualised. The belt tension wheel, Figure 19c, was made using additive manufacturing. The mechanism allowed for the adjustment of belt tension by regulating the position of two slotted members relative to two tightening bolts. Through testing in an indoor lab, the belt tension mechanism seemed to work as intended and without issues. Furthermore, an electric motor, discussed in Section 3.1.7, replaced one of the plastic wheels from the previous suspension prototype, see Figure 19d. Other significant differences between this prototype and the previous suspension prototype included a more rigid structure with more accurately manufactured parts and a different spring suspension setup. More specifically, the integration of members resembling springs linking the upper horizontal members and an inner member connected to the two side plates where the axles were mounted.



(a) Suspension set-up in laser-cut MDF.

(b) Sketch of the suspension with belt tension mechanism.

(c) Belt tension mechanism with wheel inside suspension module.

(d) Suspension module with electric motor integrated.

Figure 19: Suspension prototype in laser-cut MDF.

3.1.7 Electric motor drive system and integration into suspension prototype.

Electric drive system

The drive system used in this project was an electric battery driven bicycle hub motor controlled through a wired control unit. The motor, shown in Figure 20a, was a geared rear hub DC motor or the type Bafang RM G060.250/350/500.DC with 36 Volts and 250 Watts power output. The maximum torque and rotational speed were stated to be 80 Nm and 290 RPM respectively. The battery, shown in Figure 20b, was a Shanshan Hailong Battery case with 52 Samsung-29E 18650 rechargeable Lithium battery cells with the following specifics: 36 Voltage output, 14.5 Ah, 522 Wh Power capacity. The weight of the motor was 3.1 kg and the weight of the battery was 3.4 kg. The motor speed was regulated with a thumb throttle on the motor control unit. In addition to the thumb throttle, the control unit also included a control panel and a control unit screen. The control panel was used to switch the drive system ON and OFF, and the control unit screen showed the speed of the motor adjusted for a 26” bicycle wheel. [3]

(a) Bafang RM G060.250/350/500.DC 36V 250W electric bicycle hub motor.

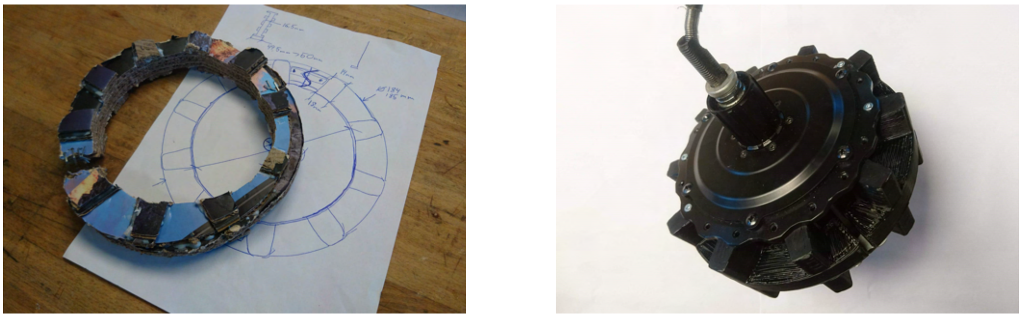
(b) Battery with wiring and motor control unit.

Figure 20: Electric drive system with Figure 20a showing motor and Figure 20b showing battery and control units with battery in top left, motor control unit with control panel and screen in centre and thumb throttle for speed regulation in bottom right.

Source: [3]

Cogwheel design and construction

A cogwheel was designed and mounted on the outside of the motor to ensure proper power transfer from the motor to the belt. The cogwheel dimensions were taken from the plastic snowblower wheels used in the initial suspension mock-up prototype. To facilitate a good gear meshing, the same pitch and outer diameter and number of teeth was used for the cogwheels made for the electric motor. First a cardboard cogwheel was created to test how a cogwheel might be mounted on the motor. Mounted on the motor, the cardboard version also provided valuable insight into how the electric motor cogwheel would mesh with the belt teeth during rotation. Figure 21a shows the cardboard cogwheel prototype, without hub motor, on top of a drawing with cogwheel dimensions. Based on the cardboard prototype, the cogwheel teeth were widened to increase the contact area between belt teeth and cogwheel teeth. Finally, a cogwheel was designed in CAD and produced in two pieces using additive manufacturing. The two parts of the cogwheel mounted on the electric hub motor are shown in Figure 21b, visualising a small gap between the two parts of the cogwheel. However, this gap did not seem to influence the gear meshing in early testing in the lab.



(a) Cardboard cogwheel prototype and reference drawing of cogwheel dimensions.

(b) Electric motor with cogwheel made using additive manufacturing.

Figure 21: Electric motor cogwheel prototypes.

3.1.8 Height adjustment of belt and motor module

A height adjustment mechanism to raise and lower the motor and belt was implemented in the design of the CCSS. This was done to enable the belt to be lifted out of contact with the ground if necessary. This could be the case on long flat parts of ski trails to, for example, save electricity or in the case of a flat battery. To make the system as simple and fail proof as possible, e.g. not dependant on electricity, a mechanical manually operated system was desired. Should the user not be able to operate the manual mechanism or want an automatic system, the system could be altered to facilitate this.

Lever arm mechanism for height adjustment

At first, a height adjustment mechanism controlled manually with a lever was developed and investigated with prototypes. The first small scale paper model and the Lego models described earlier integrated this type of mechanism. The mechanism is explained in Figure 22, with the mechanism in lifted and lowered position. Through further investigation with the full size chassis paper model and the wood chassis prototype, the lever mechanism was found to have several issues. Firstly, the lever arms would be hindering natural poling motion for the user. Secondly, the set up did not create a stiff suspension structure to limit yaw in the motor module. In addition, there would most likely be large forces producing large moments on the horizontal pivot axle requiring thorough stress and strength analysis, possibly also resulting in increased weight to handle the forces.

(a) Height adjustment mechanism in lifted position on small scale paper model.

(b) Height adjustment mechanism in lowered position on small scale paper model.

Figure 22: Height adjustment mechanism integrated on a small scale paper model.

Turning screw concept for height adjustment

In the light of the knowledge gained with the lever mechanism prototypes, a suspension frame concept was developed to be implemented for height adjustment. Figure 23 shows some of the frame structure concepts. Top left (1) shows a mechanism where a turning screw is used to raise and lower the module. On the right (2) shows how the mechanism could easily be altered by implementing a motor or actuator to accommodate automatic operation. Bottom left (3) shows a gear mechanism to move the frame to raise and lower the module. Although promising, these concepts were not continued because they did not sufficiently solve the issues with yaw and frame stiffness previously discussed.

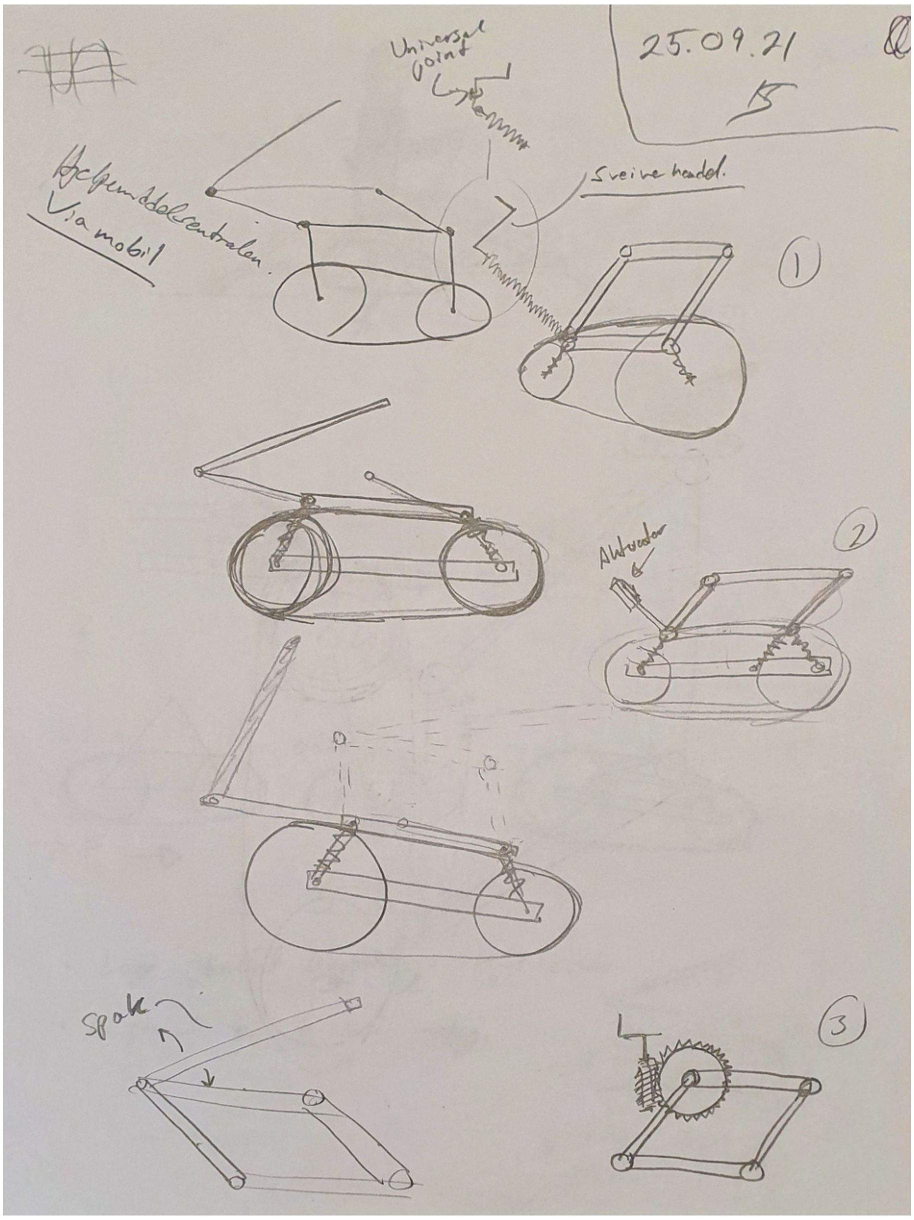


Figure 23: Sketches of concepts for height adjustment module.

Sliding mechanism concept for height adjustment

To stiffen the height adjustment and suspension frame and avoid yaw, a new concept with a double frame was developed. A sketch of the developed concept with a sliding mechanism is shown in Figure 24. The mechanism works by sliding the top left part of the structure along a straight and smooth member to raise or lower the motor module. Holes in the straight member allowed the mechanism to be locked in several positions. On the bottom and right side of the sketch, a lever handle is shown. This was designed to be used to engage the locking mechanism.

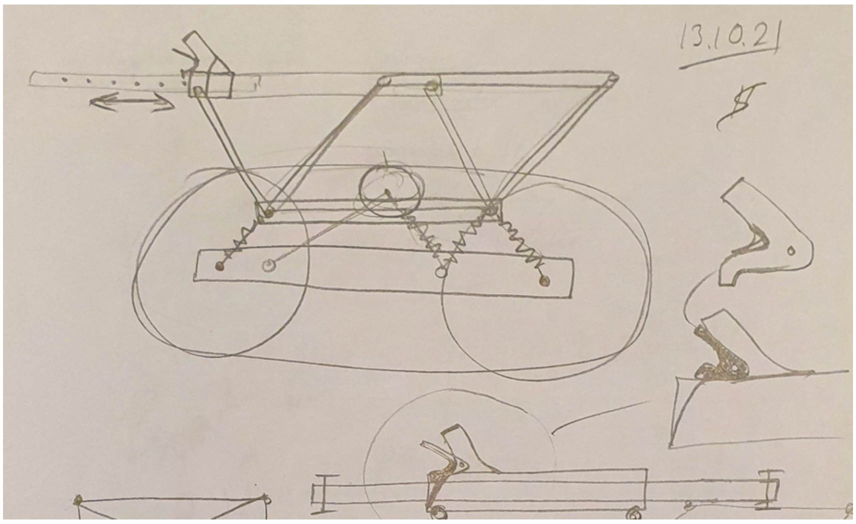
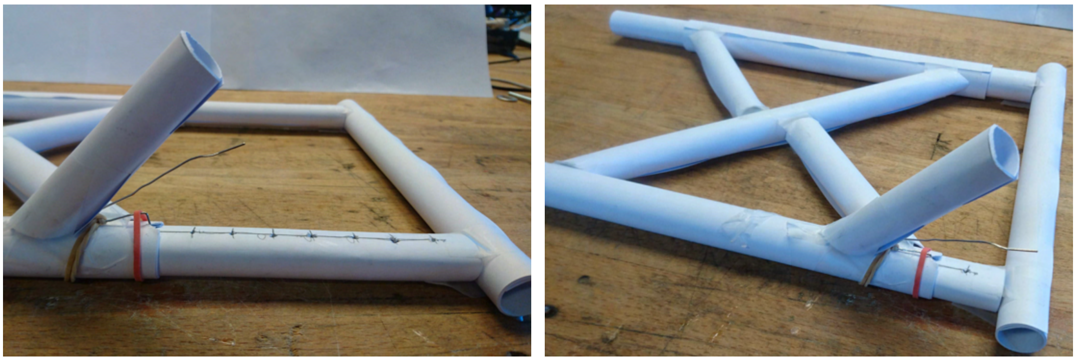


Figure 24: Sketch of a sliding mechanism for height adjustment module.

Based on the concept sketches, a paper prototype was constructed to test the functions. Figure 25 shows the paper prototype of the sliding mechanism with a paperclip and rubber bands used for the lever handle mechanism. With holes in the paper cylinder, the lever handle mechanism locked the sliding movement of the structure. This concept seemed very promising and a more rigid prototype was therefore developed to test the concept combined with other parts and functions on the wood chassis prototype.



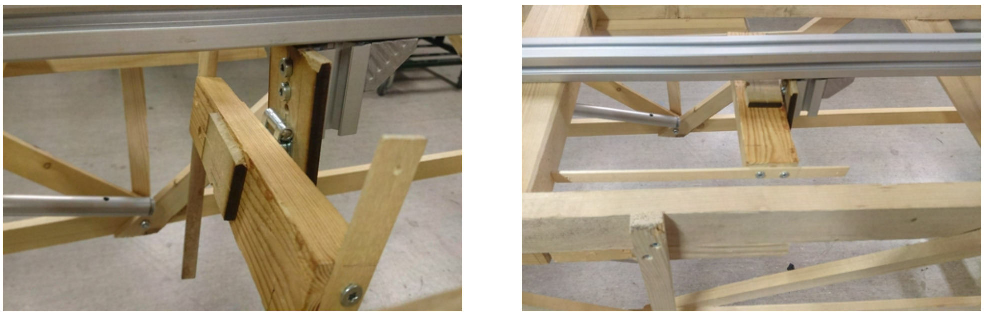
(a) The sliding mechanism paper prototype in paper elongated.

(b) The sliding mechanism paper prototype in paper in compact position.

Figure 25: The sliding mechanism prototype with simple lever handle and holes in member.

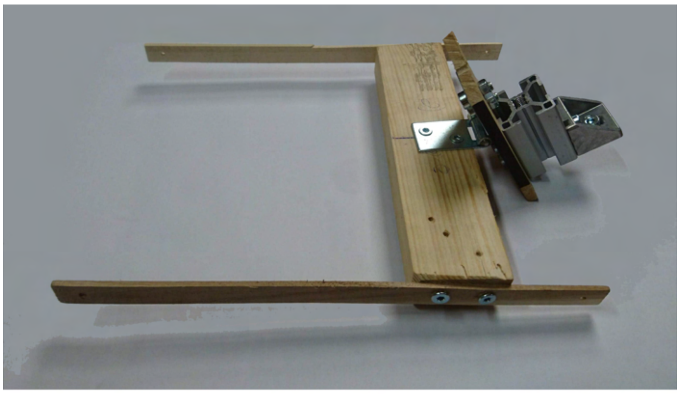
Sliding mechanism with aluminium rails for height adjustment

Before the construction of a more rigid prototype of the previously mentioned sliding mechanism, aluminium rails were discovered and tested for their possible use. A sliding mechanism with aluminium rails was constructed, shown in Figure 26. The prototype configuration with aluminium rails worked by sliding a locking piece inside a long slot in the aluminium rail. The locking piece could be fastened to inhibit sliding motion by tightening a bolt. Although the setup worked well and the long aluminium rail could be integrated as a load carrying structure in the chassis, there were issues regarding the operation. The mechanism for locking and sliding the locking piece along the aluminium rail was difficult to operate because it required a hex key. Furthermore, the locking piece fell out of the aluminium rail slot several times, resulting in the whole prototype dividing in two. The aluminium rails were therefore not continued, but instead the knowledge gained was noted for the possible reuse and reintegration of the aluminium rails in a future chassis.



(a) Sliding mechanism with aluminium rails in lower position.

(b) Sliding mechanism with aluminium rails in raised position on wood chassis.



(c) Sliding mechanism isolated without aluminium rail on wood chassis.

Figure 26: Height adjustment concept prototype with aluminium rails.

Sliding mechanism prototype for height adjustment with crutches, cardboard and wood sticks

Continuing the sliding mechanism concept tested with the paper and paperclip prototype previously discussed, a prototype was constructed with crutches, cardboard and wood sticks. The prototype integrated on the wood chassis is shown in Figure 27. The crutches are connected to the chassis in front and rear. Two cardboard boxes with holes are mounted round the crutches and slide along them. Bolts are used to lock the cardboard boxes in positions along the crutches. The suspension frame connecting the belt and motor module to the chassis is connected both to the chassis and the cardboard boxes. By sliding the boxes along the crutches, the belt and motor module is raised or lowered. The frame with diagonal cross members limits the sideways movement of the belt, only enabling up and down movement. Yaw motion in this suspension frame is also limited with this construction.

(a) Sliding mechanism for height adjustment with cardboard and crutches mounted on wood chassis, top view.

(b) Sliding mechanism for height adjustment with cardboard and crutches mounted on wood chassis, inside view.

Figure 27: Sliding mechanism for height adjustment using crutches, cardboard and wood sticks integrated on wood chassis.

3.1.9 Steering module

Steering capabilities was one of the most important features wanted to be implemented into a CCSS, and therefore a steering module was developed and constructed. Inspiration was taken from the Exero Spike [27], Beitoskilator [5] and skateboard trucks in the design of the steering module. In the design process of the steering module a similar version of the steering module used on the Exero Spike was supplied by Exero Technologies and integrated on the chassis. It was a steering module with axles meant to be used with wheels.

Fixed wood module

Initially, the chassis design was adjusted and the steering modules mounted on the front and rear. Figure 28 shows the steering module mounted on the chassis. Wood was cut out to angle the steering module correctly. The steering module angle of the Exero Spike [27] was used as reference. Through initial lab tests the connections between the wood parts of the steering modules were not stiff enough, resulting in play. Even though the steering module did work for steering, this meant that the steering module did not function properly and with less movement than necessary.

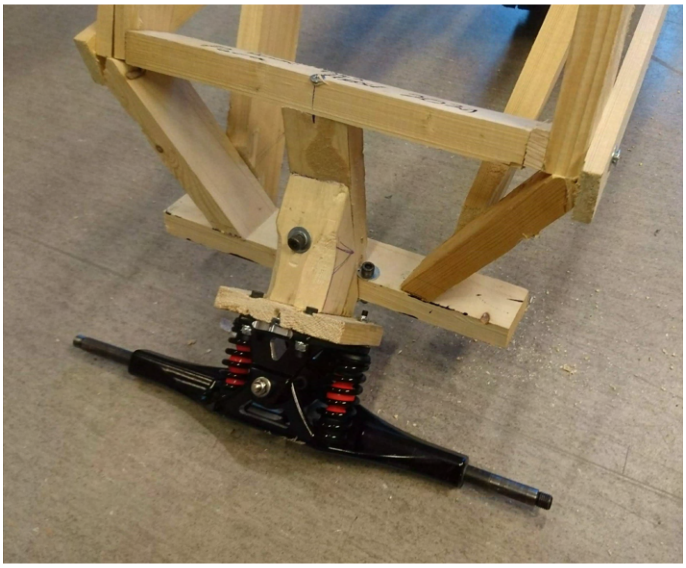
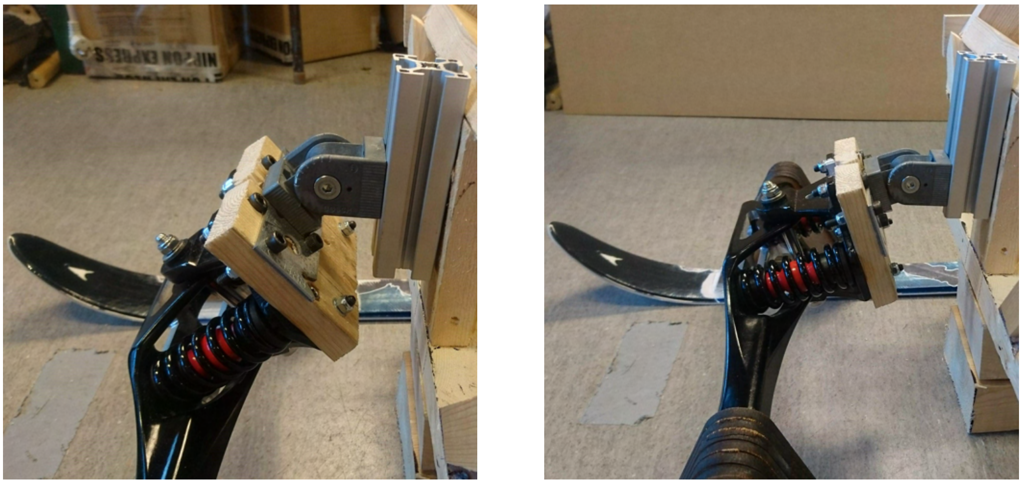


Figure 28: Steering module mounted on chassis.

Adjustable aluminium rail module

To solve the problem with the unwanted play between the wood parts of the steering module other possible solutions were investigated. A new adjustable steering module was constructed using a metal joint that could be locked and an aluminium rail. This adjustable set up, shown in Figure 29, enabled different angles for the steering module. The different angles could potentially be used to adjust the sensitivity of the steering to accommodate individual user needs. Initial tests of the adjustable steering module were promising, but when mounted on the chassis and higher loads were applied, the metal joint was not strong enough to handle the forces. The joint worked as a hinge at higher loads and could not be used to transfer the necessary loads. This adjustable set-up with aluminium rail and metal joint was therefore not continued.



(a) Adjustable steering module higher angle setting.

(b) Adjustable steering module lower angle setting.

Figure 29: Steering module with adjustable aluminium rail and joint.

3.2 Preliminary final prototype

The final prototype was built up of improved prototypes of the ones discussed in the previous section, in addition to a seat. The final prototype CCSS, Figure 30, was measured to be 170 cm from front to rear without skis and 203 cm with skis. The widest part of the CCSS was the seat at 38 cm, which was mounted 60 cm above the ground. At the highest possible setting the belt had a 5 cm clearance to the ground. The final prototype CCSS could be divided into 6 sections: Chassis and sitting position, Steering module, Height adjustment module, Suspension module, Battery and wiring, and Motor control. Each of the sections are explained further in individual subsections below.

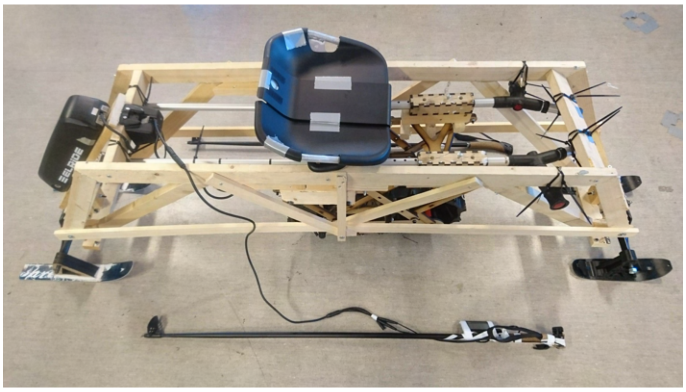


Figure 30: Final prototype in lab.

3.2.1 Chassis and sitting position

The wood chassis was the structure used to mount all the sections on, as well as the structure that created the sitting position. On top of the chassis a seat was mounted. The seat was of the same type used on the Exero Spike Snow [28]. The seat could be moved back and forth on the chassis. The legs rested on the chassis. The final prototype with a user in a lab is shown in Figure 31. By moving forward on the chassis, the feet could rest on the lower horizontal member at the front of the chassis. An alternative position was to sit with the feet resting where the calves of the user shown in the figure are resting. The sitting position was, not surprisingly, not the most comfortable, as the main focus of the development project was on other aspects such as the steering module, height adjustment module and motor module.

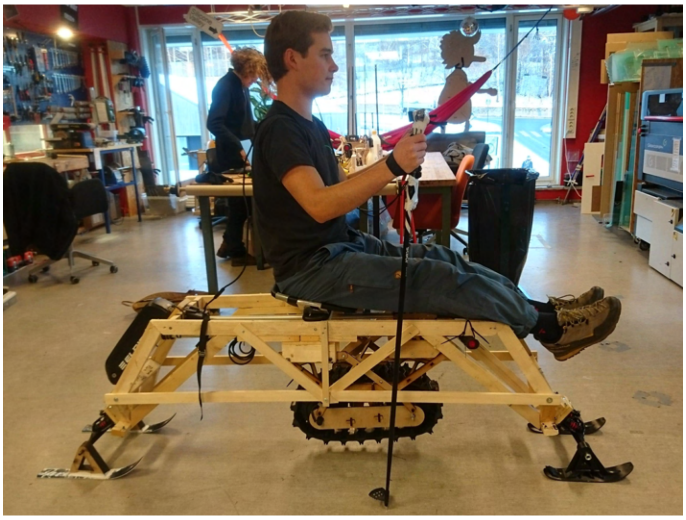


Figure 31: Final prototype with user in lab.

3.2.2 Steering module

The steering module for the final prototype was an improved version of the fixed wood prototype steering module with skis mounted on the wheel axles. To increase the stiffness and avoid play, the parts were glued together and further reinforced with steel bands and additional screws. The skis used were supplied by SIAT, NTNU. The front pair was additive manufactured in plastic and the rear skis were made from the front part of normal cross country skis with brackets fastened to connect them to the axle. Bolts were used for the front skis and rubber bands were used for the rear skis to avoid the skis from sliding off the axles. The steering modules, front and rear, with skis are shown in Figure 28.

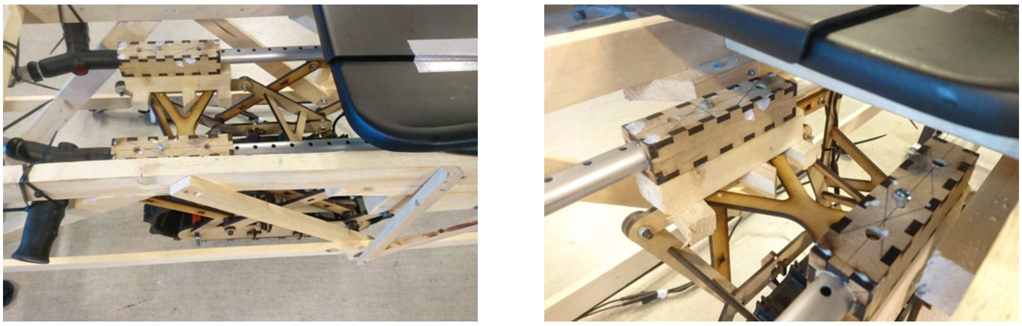
(a) Front steering module with skis on final prototype.

(b) Rear steering module with skis on final prototype.

Figure 32: Front and rear steering modules with skis on final prototype.

3.2.3 Height adjustment module

The height adjustment module installed on the final prototype was an upgraded version of the prototype made with cardboard and crutches. The crutches were firmly and more accurately placed on the chassis. Instead of the cardboard boxes, laser-cut MDF boxes were used. The suspension module was connected to the height adjustment module and chassis via custom-made blocks of wood. This resulted in a more rigid structure. M6 bolts through holes in the laser-cut MDF boxes and crutches were used as pins to lock the module in specific positions. Raised and lowered positions of the module are shown in Figure 33.



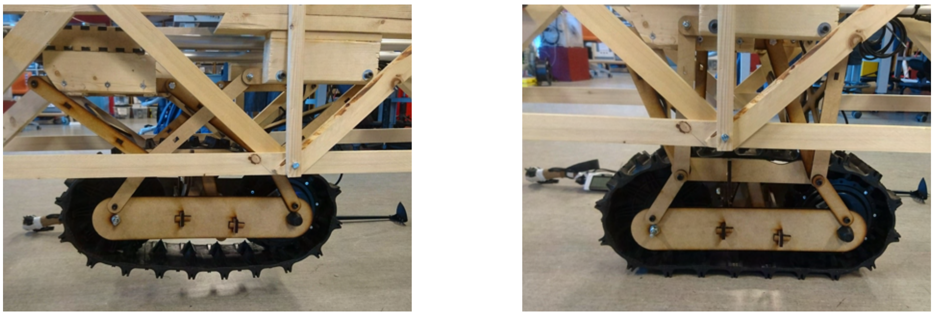
(a) Height adjustment module in raised position on final prototype.

(b) Height adjustment module in lowered position on final prototype.

Figure 33: Height adjustment module on final prototype.

3.2.4 Suspension module

The belt and motor suspension module was mounted on the chassis via the height adjustment module. A wider outer rigger was added on the suspension module, widening the module to make more space for bolts when raising and lowering the module. Figure 34 shows the suspension module in raised and lowered position and how it was mounted to the chassis. The maximum raised position was limited with the front wood blocks connecting the suspension frame to the MDF boxes on the height adjustment module. This avoided the belt track lugs from hitting the cross members on the suspension frame.



(a) Suspension module in raised position on final prototype.

(b) Suspension module in lowered position on final prototype.

Figure 34: Suspension module on final prototype.

3.2.5 Motor control unit mounted on ski pole

To facilitate motor control during skiing, the motor control unit was mounted on the right ski pole. Figure 35 shows the right ski pole with the motor control unit attached. At the bottom, the screen was placed, showing whether the motor was ON or OFF, the distance and speed adjusted for a 26” wheel and the battery power status. The thumb throttle was placed at the top of the ski pole, controlled using the thumb. Between the screen and thumb throttle, the control panel was placed.

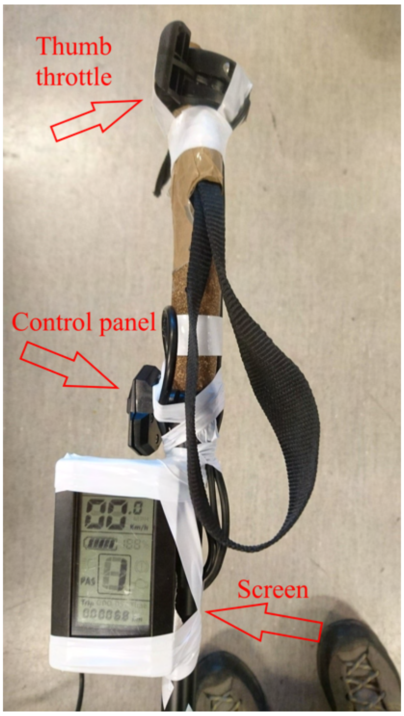


Figure 35: Motor control unit on ski pole.

3.2.6 Battery and wiring on chassis

The battery was placed at the rear of the chassis to increase the weight at the rear, thereby improving the weight distribution on the skis to be more even. Figure 36 shows the battery mounted on the rear of the chassis. Cables between the motor and battery were attached to the chassis using strips. The cable from the battery to the control unit on the ski pole was loose to allow for free arm movement. A strap was used to fasten the cable to the overarm of the user to keep the cable out of the way and avoid it getting caught in e.g. the belt or other moving objects. On the cable between the battery and the motor control unit there was a link working like a safety mechanism. In case the user fell off the CCSS, the cable would detach at the link, turning the motor OFF. Furthermore, the battery was placed in such a way that it could easily be removed to charge disconnected from the chassis and to reduce the weight of the CCSS when in transport.

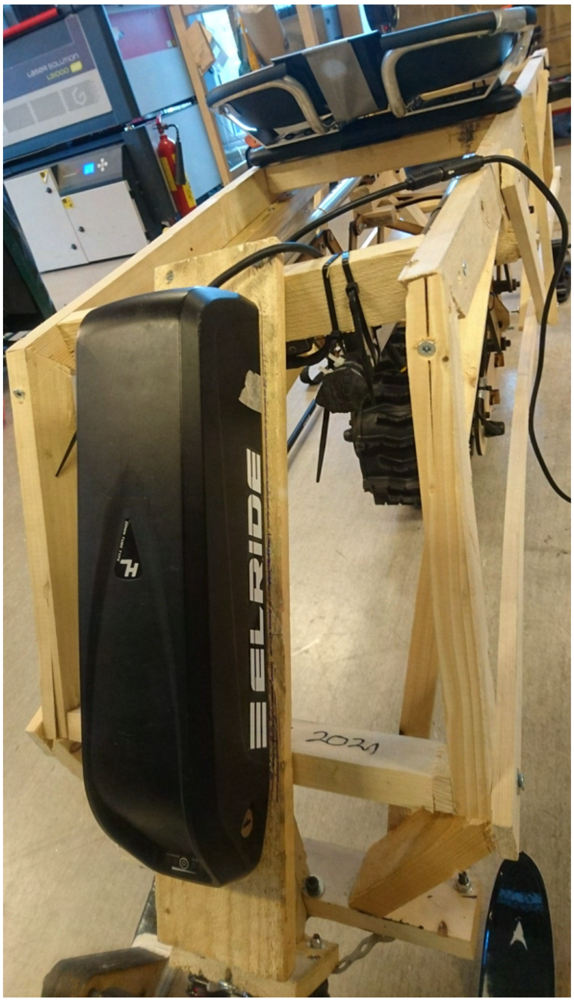


Figure 36: Battery mounted at the rear of the chassis with cables attached to chassis.

3.3 Testing and discussion of final prototype in specialisation project

3.3.1 Testing of final prototype in the specialisation project

The final prototype was tested in a cross country ski trail at Granåsen in Trondheim. Three participants tested the CCSS prototype. One of the participants also logged some of the testing using a GPS watch and a heart rate monitor chest strap to collect data. The CCSS was tested in the following scenarios: Flat ground, up and down a 5° hill, up and down a steep slope approximately 10°, in classic ski tracks and in right and left turns. The conditions were good, with an air temperature of -3°C and fairly compact snow. The trail seemed to have been used a little since it was groomed.

Flat ground test

First the CCSS prototype was tested with the belt in raised position by double poling. The CCSS felt quite heavy to move with no propulsion assistance from the motor. The user was not fastened to the seat with a strap and had to rely on gravity to avoid exiting the sitting position while double poling. When the user managed to get up to some speed, the double poling felt easier and the CCSS maintained a steady speed. Additionally, the CCSS turned slightly to the right when the user sat in a neutral position.

Secondly, the CCSS was tested on flat ground with the belt lowered. The height setting with 6 holes visible on the crutches was used to gain good traction. It was extremely difficult to move the CCSS by double poling without any assistance from the motor because the motor module worked like a brake. However, with the motor propulsion assistance, the CCSS quickly gained speed. No additional double poling was necessary to make the CCSS move. With maximum motor power and double poling the CCSS reached speeds of roughly 10 km/h. Figure 37 shows the testing on flat ground with motor propulsion and double poling.

Figure 37: Double poling with motor propulsion on flat ground.

Uphill and downhill 5° slope

In the second scenario the CCSS was tested up and down a 5° hill with the belt module lowered. The height setting with 6 holes visible on the crutches was used to gain good traction. First, the user was double poling in combination with propulsion assistance from the motor. Ascending the hill was no problem and the user was not exhausted at the top. On the descent of the hill, the motor provided controlled braking and the user could easily control the desired speed with the use of the thumb throttle. Figure 38 shows the CCSS tested by the user down a small slope. In a second ascent, the user was not double poling and relied only on the propulsion from the motor to get up the hill. The CCSS managed to climb steadily up the hill, only stopping once because the belt spun for some unknown reason.

(a) User double poling with motor propulsion assistance on flat ground before small slope.

(b) CCSS with user leaning to the left to maintain straight forward travel down small slope.

(c) CCSS with user in descent down small slope.

(d) At the bottom of the small slope the user was leaning to the left to steer the CCSS straight forward.

Figure 38: CCSS tested down a small slope with the belt lowered for braking and to control speed.

Uphill and downhill steep slope approximately 10°

Furthermore, the CCSS prototype was tested in a steep hill approximately 10° with the belt in lowered position. The height setting with 7 holes visible on the crutches was used to gain good traction. Downhill the motor managed to brake and fully stop the CCSS without problems. The descent felt safe and controlled. Afterwards, an attempt was made to ascend the same hill with double poling and propulsion assistance from the motor. With maximum motor power the CCSS just barely managed to climb the hill. Figure 39 shows the user double poling up the steep hill with motor propulsion assistance. However, due to snow conditions varying from compact to loose, the belt track spun several times and had to be lifted past the loose snow patch. The double poling was very exhausting.

Figure 39: Double poling with motor propulsion up steep hill.

In classic ski tracks

Later, the CCSS was tested in the classic ski tracks with the belt in lowered position. The height setting with 5 holes visible on the crutches was used in the classic ski tracks to gain good traction. Both when using only the propulsion from the motor and when in combination with double pooling, the CCSS worked well in the classic ski tracks. However the skis were placed roughly 5-10 cm too far apart for both skis to properly fit in the classic ski tracks. Furthermore, the belt left a mark on the middle of the classic ski tracks. Further investigations in a variety of snow conditions are needed to assess the potential damage to the middle of the classic ski track as a result of the belt pressure.

Left- and right-hand turns

Finally, the CCSS was tested through left- and right-hand turns, with the belt in raised and lowered positions. The CCSS performed well, especially in turning right. Turning left proved more difficult, but it was manageable. In left-hand turns the chassis creaked and seemed less stable. The left ski pole was occasionally used to maintain balance and avoid falling over when turning hard to the left. Furthermore, when turning hard to either side, the rear ski on the opposite side of where the CCSS turned was lifted and lost ground contact. This was especially the case when the user was leaning forward when performing the turn. This resulted in worse turning performance.

3.3.2 Evaluation of the final prototype tested in the specialisation project

Chassis and sitting position

The chassis was strong and the CCSS felt stable when sitting on it, both in motion and standing still, even though the user sat quite high above the ground compared to conventional CCSSs. The seat worked well for sitting, although the sitting position was not very comfortable. The calves rested on one of the horizontal cross members of the chassis. A belt strap and better leg and foot support could improve the experience. In addition, the sitting position with adjustment possibilities for seat angle and leg and foot position would be desired. Furthermore, the CCSS chassis should be optimised to be lighter, stiffer and stronger to support more load without bending. This is especially relevant when turning hard. With short skis mounted on the CCSS, the chassis can be shortened significantly thereby saving weight and increasing strength.

Steering module and skis

The steering module worked as intended, although turning slightly to the right when the user sat in a neutral position. This was most likely because the steering module was mounded slightly askew on the chassis or because the wood members on the chassis were in fact not perfectly straight. Figure 40 shows the steering module not mounted perfectly straight on the chassis. By building a more rigid chassis and making sure the steering modules are mounted correctly, this can be avoided in future prototypes.

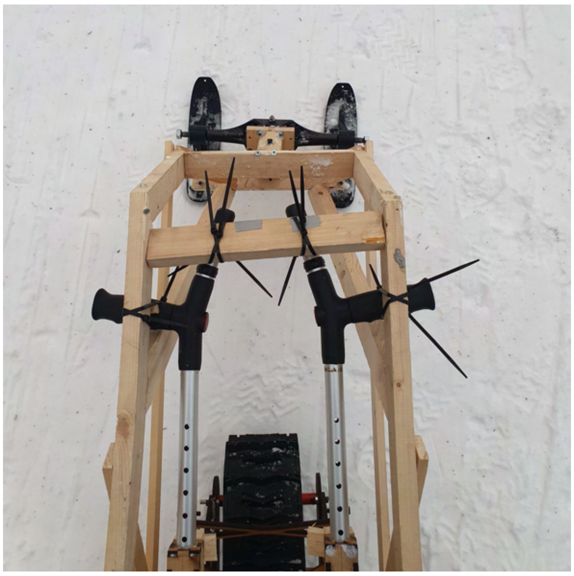


Figure 40: Steering module not mounted perfectly straight on chassis.

In the classic ski tracks both the skis on each steering module did not fit in the tracks at the same time. This can be solved by developing skis that are mounted closer together on the steering modules. However, to enable both the skis to fit in the classic ski track at the same time and ensure high stability with skis placed far apart may seem contradictory. This could possibly be solved by having outrigger skis to maintain balance, while also adjusting the main skis to have the correct distance to fit in the classic ski tracks. Future research is needed to evaluate whether outrigger skis are necessary to maintain balance and a steady CCSS, or whether this can be solved by, for instance, lowering the centre of gravity.

Height adjustment module

The height adjustment mechanism worked well to adjust the height during testing. However, a better mechanism should be developed because the user had to step out of the CCSS every time the height of the belt module was adjusted. This can be avoided if the lever to operate the height adjustment mechanism is more accessible for the user. Furthermore, the midpoint on the crutches where the suspension module was connected bent slightly upwards when the motor accelerated. This was due to the increased forces applied to the crutches through the suspension frame members during loads on the motor. The result of the bending was a reduced ground pressure between the belt and the ground. This did not seem to greatly affect the traction, but might however have played a role when the belt track lost traction up the hills.

Suspension module

The suspension module worked surprisingly well, given that it was constructed primarily using laser-cut MDF plates. During the testing, however, one of the members in the suspension module broke. This is shown in Figure 41. This did not greatly affect the function of the suspension module, but resulted in a less stiff structure and in some situations less even pressure distribution between the belt track and the ground. Furthermore, during high loads on the motor, the motor axle twisted and as a result disconnected the power, resulting in a motor stop. This happened because the motor axle was mounted to MDF plates with a locking groove to avoid axle spin that did not support the high loads. Future versions should be designed with this in mind.

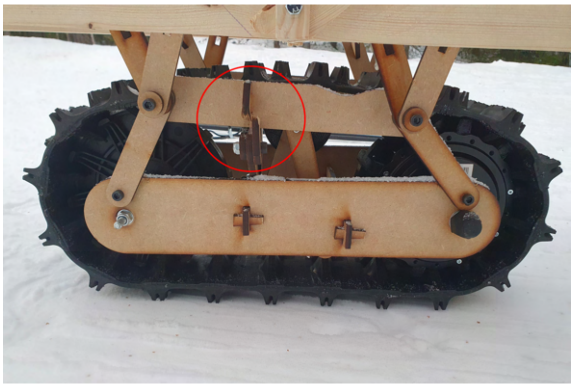


Figure 41: Broken part on suspension module during testing.

During belt rotation the cogwheel seemed to sometimes mesh badly with the belt teeth. This was maybe because of the screws and metal plates used to connect the two parts of the motor cogwheel. Other reasons for the sometimes bad meshing may be a result of a slightly larger distance between the teeth of the motor cogwheel across the connection point compared to the distance between the rest of the teeth. Figure 42 shows the connection of the two motor cogwheels and a gap between the two cogwheel parts. Future versions of the motor cogwheel should take this into account.

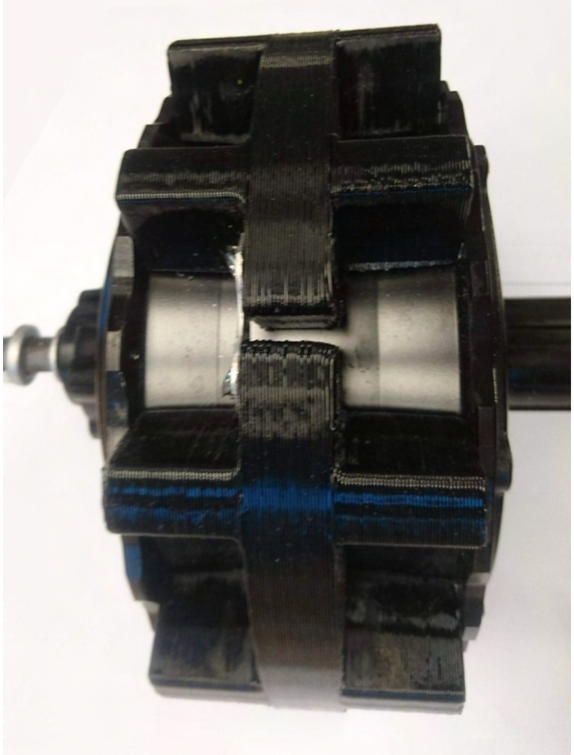


Figure 42: Connection of the two motor cogwheel parts.

Motor and motor control

During the testing the motor performed well, showing no signs of overheating or development of heat. This was controlled and measured by touching the motor casing to feel the temperature. The motor seemed to supply adequate amounts of propulsion assistance during testing. To ensure even and reliable propulsion assistance during operation, a better suspension system should be prioritised over a more powerful motor.

The motor control worked well during the test, even though improvements to the motor speed regulation would ensure a more comfortable and user-friendly operation. While wearing thin gloves, the thumb throttle was quite easy to regulate. On the other hand, when wearing mittens the thumb regulation proved more difficult. The thumb throttle also required fine and accurate muscle movements in the thumb to operate. The ON and OFF button on the control panel was easy to operate, but the screen was difficult to use. This was especially the case when double poling, as the screen was attached to the ski pole. On a final note, the cable between the battery and the control unit on the ski pole did not get caught by any of the moving parts and was not in the way during double poling. However, the strap used to keep the cable in place was necessary and attention was needed to make sure the cable was in an OK position during double poling. A wireless connection between the control unit and the battery and motor or better and easier cable attachment to the user instead of a simple arm strap could solve this issue.

3.3.3 Feedback from test participants

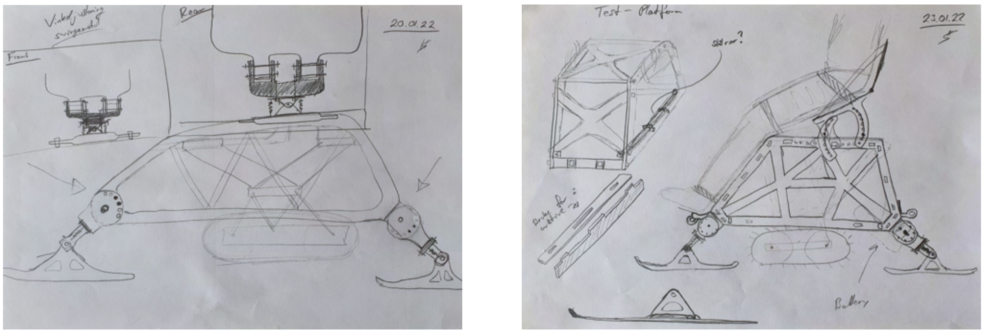
The test participants were impressed with the prototype, but also supplied some points of improvement. Firstly, the test participants noted that the CCSS prototype felt stable and sturdy even though it was quite high compared to other conventional CCSSs. Secondly, the test participants felt safe sitting on the CCSS, as long as the belt was in contact with the ground because the motor module provided propulsion and braking assistance. Thirdly, the test participants remarked that the steering worked well, although the CCSS turned slightly to the right when sitting in neutral position. Furthermore, the test participants noted that the sitting position was not very comfortable. The top horizontal member at the front of the chassis was in the way, hindering a more comfortable sitting position. The sitting was not bespoke to the individual test participants, resulting in a less comfortable experience. The test participants wore different gloves and mittens, resulting in different motor control experiences. Although the thumb throttle worked and was easy to use, there were some issues in fine tuning the speed while skiing. This was especially the case when using thick mittens. The test participants indicated that the CCSS prototype was heavy when double poling without motor propulsion. Finally, the test participants mentioned that the CCSS could be lighter and easier to transport.

4 Design and construction of test rig

Based on the findings from the specialisation project in autumn 2021 [23], a test rig was initially designed to test out several possible ideas and design configurations in a fast and simple way. Primarily different versions of suspension and steering mechanisms would be tested. The plan and goal was to find the most ideal configurations of steering, suspension and possibly other unanticipated findings before then constructing a chassis around the suspension and steering, while also accommodating the highest possible comfort for the user.

4.1 Test rig design creation

The test rig design was developed with one main purpose; to facilitate testing of suspension and steering designs. For this reason, the test rig was designed concurrently with the suspension and steering configurations. In Figure 43 two sketches of early test rig designs can be seen. The test rig was not meant to be used for more than testing and was therefore designed to be simple and easy to assemble. A more thoroughly designed chassis structure would be developed later in the process to accommodate higher comfort for the user, as well as a lightweight structure. The test rig designs are based on mounting the steering and skis at each end, front and rear, and mounting the suspension inside the frame. This was done based on the promising findings of the prototype developed in the specialisation project in autumn 2021 [23]. When the desired suspension and steering modules had been developed and tested using the test rig, a more advanced frame construction would be designed. Several possibilities were thought out, including welded aluminium tube space frame, composite shell structure and weight optimised aluminium frame cut from plates, similar to the test rig structure. The future frame was planned to be constructed using topology optimisation and additive manufacturing of polymer material, potentially reinforced with carbon fibre particles or coated with composite to increase strength. Being able to create a 3D-printed chassis would allow for custom shaped frames, tailored to each user or need. Due to complications related to 3D-printer capacity at the institute during this project, it is in hindsight a good thing that this approach was not further pursued.



(a) Sketch of test rig design with steering modules in focus.

(b) Sketch of test rig design with seat and steering module, to be constructed with plates.

Figure 43: Sketches of test rig designs.

A cardboard model was constructed to visualise the proposed design of the test rig and to explore possible challenges or improvements. As seen in Figure 44, the test rig was designed to be built using plates mounted to form a box-like structure. Belt, motor, suspension, seat and steering modules are not integrated on the chassis in the pictures. Figure 44b shows the cardboard model with a miniature human figure sitting on top. The design would enable a comfortable sitting position with feet lower than knees and a relatively high hip position. This would potentially result in a less stable sit-ski due to the high position of the hip. On the other hand, it could result in a better skiing experience, enabling longer skiing poles because of the higher sitting position. This could then result in better form and also longer and more powerful strokes when double poling. By placing the motor and battery low, as well as having feet positioned lower than the hips, a low centre of gravity could still maintain good balance and stability of the sit-ski. Findings from the prototype testing in the specialisation project suggests a sit-ski with a relatively high hip position is possible as long as the motor and battery are placed low enough and the distance between the skis is sufficient [23].

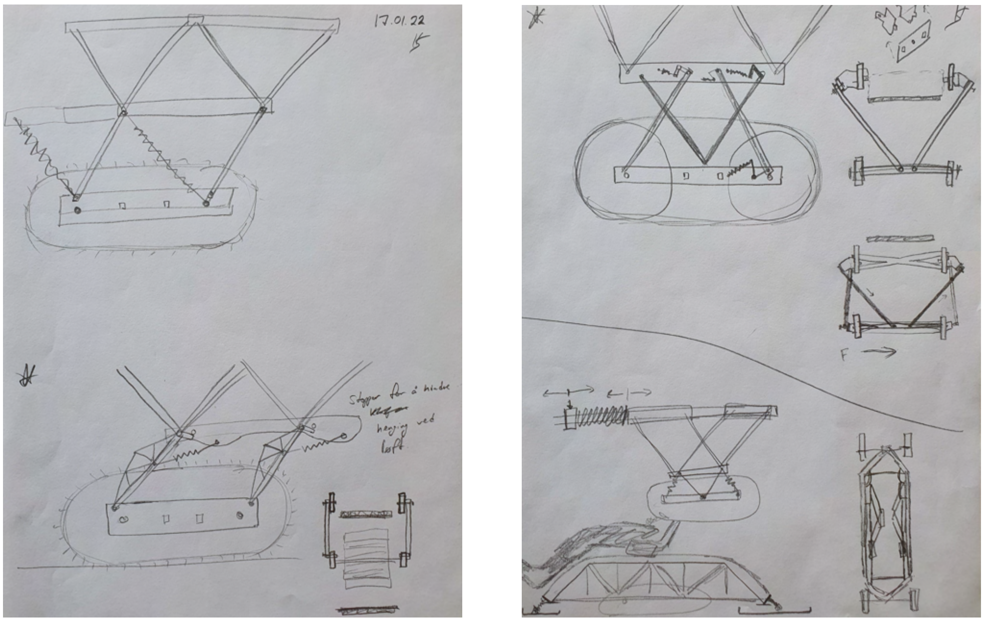
(a) Cardboard model of test rig without user figure.

(b) Cardboard model of test rig with user figure in slightly smaller scale.

Figure 44: Cardboard model of test rig with and without user figure.

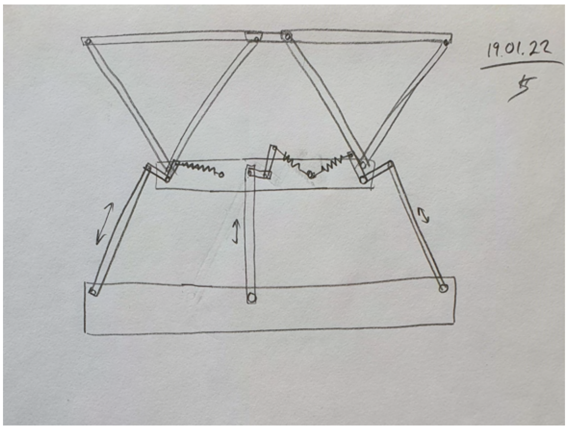
4.2 Suspension design ideas

One of the main functions of the test rig was to develop a suspension system for the belt track drive. The goal was to develop something that would both be light and simple, yet also enable good contact and traction for the belt track on the ground. Several ideas were investigated. Some ideas had already been investigated and found to not work as desired during the development of the wooden prototype and were therefore not further explored [23]. The most viable designs thought of are presented in Figure 45. Figure 45a shows the two frame suspension designs. The top is a classical compression spring suspension set up and the bottom is a simple tension spring design. These designs enable controlled up and down movements of the motor and belt module and are mounted on a frame-like link height adjustment mechanism. Two more suspension designs are shown in Figure 45b. The top suspension is a more complex suspension with several pivot points. Each arm or link between the motor and belt module and the upper frame is connected to independent bell cranks. Compression or tension springs can be used in this case depending on the geometry. To explain: X axis is the axis going from rear to front of the CCSS, y axis goes from bottom to top and z axis goes from right to left. The suspension drawn in the sketches in Figure 45 are on the x-y plane. By placing the middle links in the centre of the motor and belt mechanism, both pivot around the z and x axis is possible, resulting in 3 degrees of freedom for larger motions. This in turn may result in greater traction because the design allows for better ground contact. The complexity of this suspension does, however, result in more parts and more difficult construction. The bottom design is simpler and relies on a main suspension and pivot suspension. The main suspension moves a compression spring placed horizontally at the top of the link suspension. To enable pivot of the belt over uneven terrain, compression springs are placed front and rear. This mechanism is slightly simpler than the previous, but does only allow pivot around the z axis and has two degrees of freedom in comparison. Figure 45c shows another complex suspension design with two degrees of freedom. The middle link member works as the main suspension with hard springs, while the two link members with softer springs, front and rear, enable pivot of the motor and belt mechanism. However, this design might not be as stable as one may hope, so a physical model would be necessary to ensure it has the right rigidness and functions as required.



(a) Sketches of rear snowmobile inspired suspension.

(b) Sketches of complex suspension concepts.

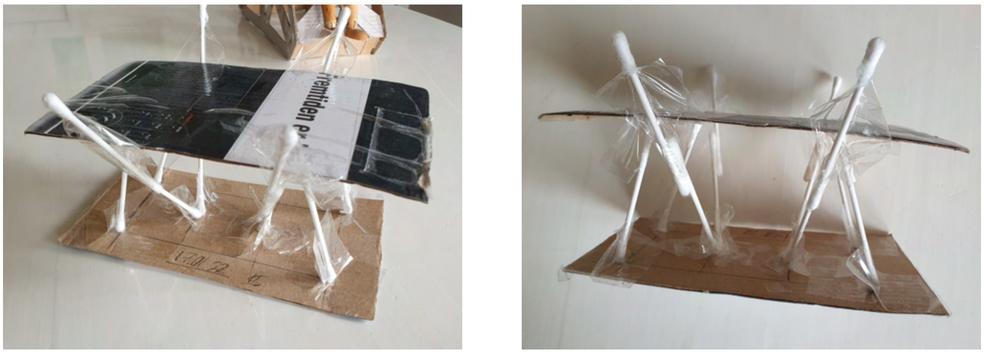


(c) Sketch of complex suspension concept.

Figure 45: Sketches of potential suspension concepts to be tested on test rig.

The most complex suspension design thought out was too complex to properly visualise with a paper sketch. A physical model was therefore constructed to visualise forces, movement of members, motion limitations and degrees of freedom. Figure 46 shows the cardboard model created to investigate the suspension design, which was constructed based on the design sketched at the top of Figure 45b. The top cardboard plate functions as the suspension mount on the cross-country sit-ski and the bottom plate acts as the frame for the motor and belt module. Each of the white sticks act as link members. The four sticks connected at the centre of the bottom plate function as the main suspension, supporting the most force. The outer four sticks act at secondary suspension to increase stability and enable movements such as pivots around the x and z axis to maintain the best possible ground contact while also restricting movements and rotation along the x and z axis and around the y axis respectively. The cardboard model proved very important and useful with providing information about the dynamics of the proposed suspension design. By moving the connection point of the sticks, the behaviour of the suspension design could be altered to be more and less rigid. By moving the connection point of the four main middle sticks outward, the suspension became less restricted in motions along the x and z axis and more restricted in pivot movements around the x and z axis. At the same time pivot around y axis became less restricted. Placing the sticks such that they were straight resulted in very little restrictions in both pivot around y axis and movement along z and x axis. This was highly undesirable.

The configuration shown in Figure 46 is the one found to enable the most movements in the desired directions while also restricting the undesired movements. The desired movements include pivot of the motor and belt module around the x and z axis and movement along the y axis. The undesired movements include pivot around the y axis and movement along the x and z axis. Due to the complexity of the suspension design constructed in cardboard, other simpler designs would be prioritised for physical testing. Later in the process, a more comprehensive design could potentially be constructed to further investigate the complex suspension design described in this paragraph.



(a) Model top side view.

(b) Model side view.

Figure 46: Cardboard and cotton buds sticks model of a complex suspension concept.

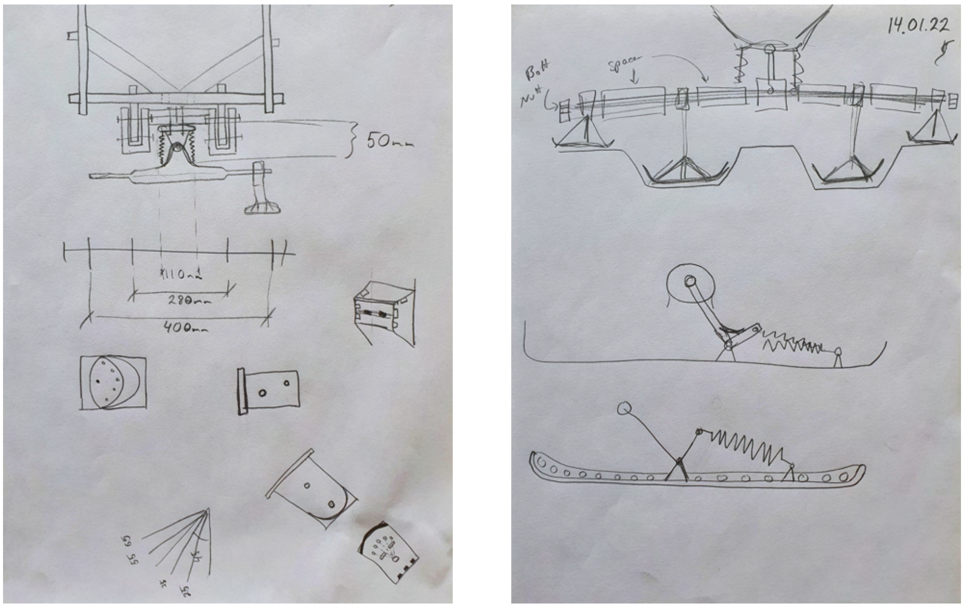
4.3 Steering and ski configuration ideas

A second vital function of the test rig was to facilitate the development and testing of a new steering and ski configuration. Through testing during the development of the Exero Spike on wheels, Berg and Fon found that an angle of 35-45° provided best turning and stability, although 35° was used in the Spike [6]. In the specialisation project the steering module trucks were mounted on the wood prototype at an angle of 45° [23]. This seemed promising in testing and provided good turning, but to ensure the best possible turning qualities, different angles should be tested. The test rig should therefore be designed to be able to test several angles of the steering modules. Furthermore, new ski configurations should be explored to investigate how best to mount the skis and whether a specific configuration could allow for skis to fit in classic ski tracks. The ski configuration used in the specialisation project placed the skis too far apart to fit in the classic ski tracks. However, by placing the skis further apart than was required to fit in the classic ski tracks, the developed prototype cross-country sit-ski proved more stable [23].

Several design ideas were explored, especially regarding the ski configuration. Figure 47a shows one of the proposed designs to facilitate testing of several angles of the steering modules. This design is further explained in the next paragraph, covering a simple cardboard model of the angle adjustment mechanism. Figure 47b shows a suggestion as to how the multiple skis could be mounted to enable skis in the classic ski tracks while also ensuring stability with skis placed wide, outside the classic ski track. The skis sketched underneath show a proposed suspension design meant for the two middle skis. This suspension design would ensure the middle skis stay in the classic ski tracks so the user of the sit-ski can follow in the tracks, like with a normal cross-country sit-ski. By having spring suspension, the skis can also be used in the skating track. The skis are then elevated to the same height as the side skis. This ensures that the belt track has the same height above the ground both in and outside the classic ski tracks.

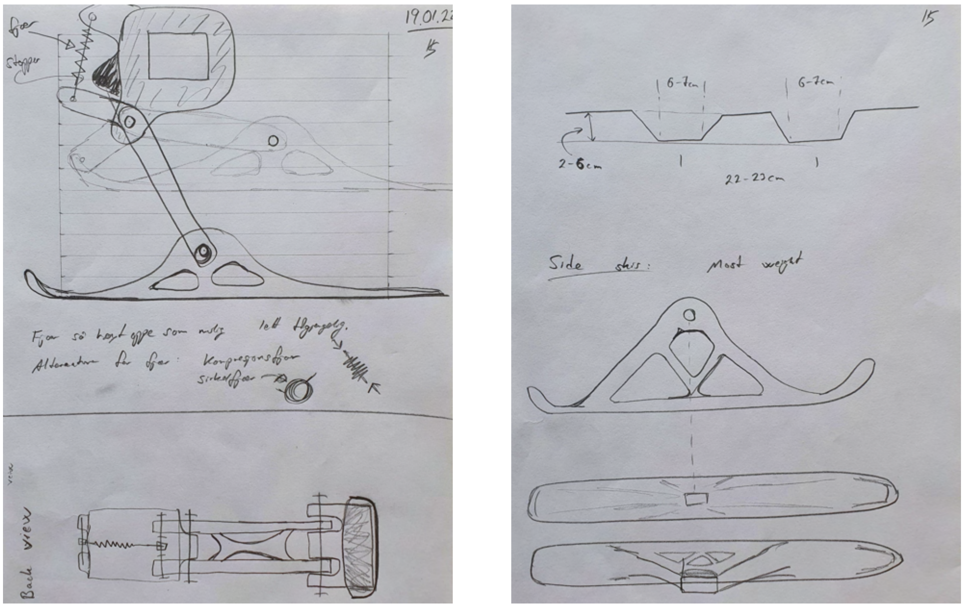
Figure 47c shows a more detailed sketch of the suspended ski in both side and rear view orientation. As seen in the upper part of the design, there is a stopper to prevent the ski from moving too far down. This is to ensure proper function of the contraption. The square hole on the mounting bracket is meant to slide onto the steering module trucks. This design could also be constructed using either a compression spring or a spiral torsion spring.

In Figure 47d, normal dimensions of the classic ski tracks in Norway and proposed design for side skis are sketched. The sketched skis can be constructed using additive manufacturing of polymer such as ABS. To achieve a low friction force between the skis and snow, glider should be applied on the skis. A strip of ski base may also be coated or glued on the underside of the skis to provide low friction.



(a) Sketch of adjustable steering module mount on test rig.

(b) Sketch of ski mount concept with multiple skis.



(c) Sketch of ski mount concept with suspension.

(d) Sketch of ski track dimensions and ski design.

Figure 47: Sketches of ski, ski mount and steering concepts.

To visualise the function and potential weaknesses of the adjustable angle design presented in Figure 47a, a very simple cardboard model was built, shown in Figure 48. The two cardboard pieces are connected through the two holes with two pins or bolts. The top piece can rotate around the top right hole to adjust the angle relative to the bottom piece and be locked in different angles with a bolt or pin. The simple model was used to help determine the geometry and dimensions of the later designed CAD-model.

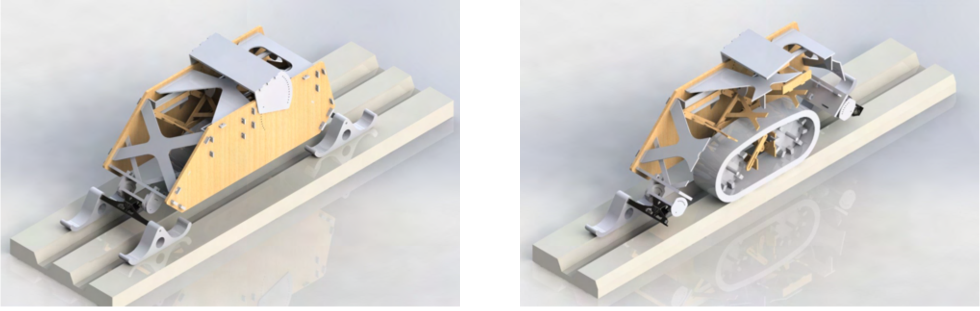
(a) Prototype in 0 degrees angle. (b) Prototype in 45 degrees angle.

(c) The two pieces of the simple prototype.

Figure 48: Cardboard prototype of adjustable steering module for test rig.

4.4 3D CAD model and physical prototype of test rig

With the use of CAD-software, a test rig was designed and parts were integrated on the test rig. Figure 49 shows the CAD model of the test rig with parts, such as steering module, skis and suspension module, integrated. A seat similar to the one used in the specialisation project would be used on the test rig. The height of the seat above the ground was designed to be 46 to 56 cm, which is a little higher than the normal seat height of roughly 30-40 cm used in other similar cross-country sit-skis [21] [28] [29] [10]. From testing with the wood prototype developed in the specialisation project, the height of the seat at 60 cm provided good stability and easy steering [23]. In addition, the feet could be placed in a more comfortable position with a larger angle in the knees and the toes close to the ground. For this reason the increased height of the cross-country sit-ski was continued in the design of the test rig. An engineering drawing of the test rig is presented in Figure 50.



(a) CAD model of test rig. (b) Cross sectional view of test rig.

Figure 49: CAD model of test rig with steering modules, skis and suspension module with motor.

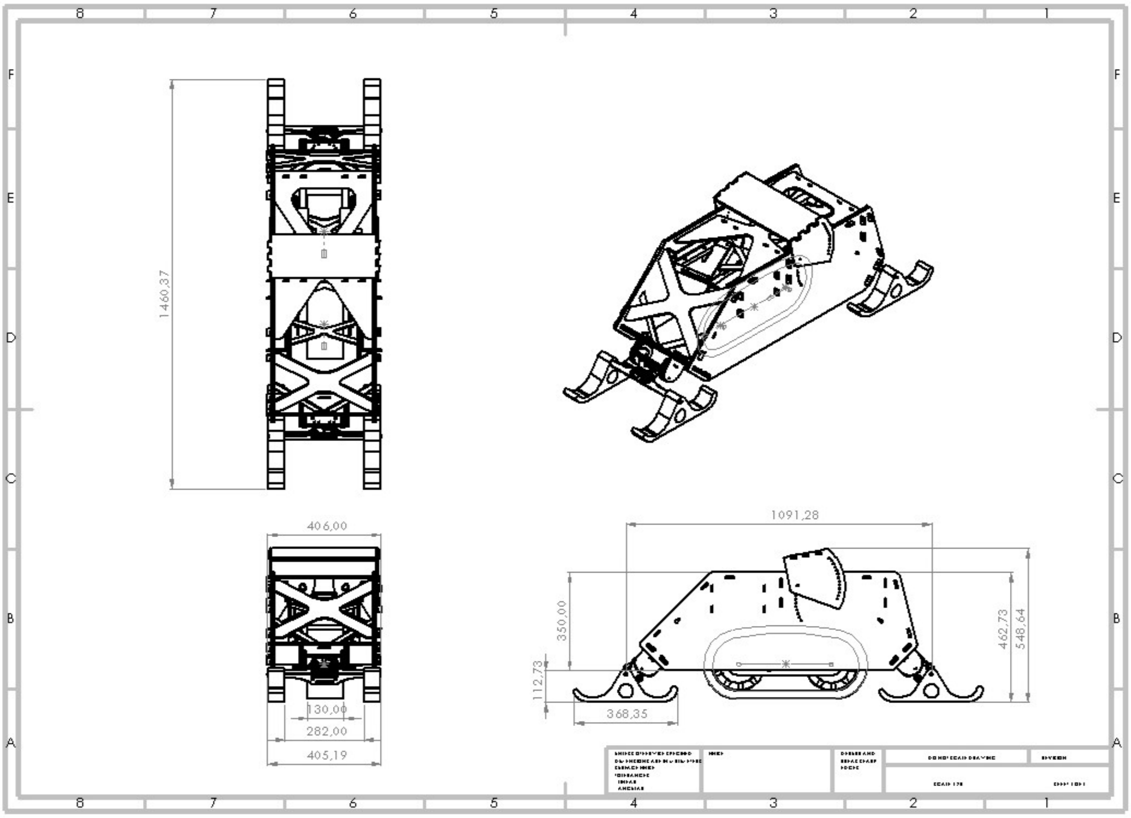


Figure 50: Engineering drawing of test rig CAD-model with dimensions.

A physical test rig was then constructed with laser cut MDF-plates to test how the steering mechanism worked at different angles, Figure 51. The plan was also to test the rig with the suspension used on the wood prototype in the specialisation project and construct new suspension configurations with height adjustment mechanisms. This way several design configurations could easily be tested quickly because the test rig allowed for changes to the individual modules.

At this point in the development, plans were changed to focus instead on the integration of motor and steering modules on the already existing Exero Spike Snow. This was decided in consultation with supervisors and was primarily because it potentially could lead to a usable product sooner and give more valuable insight for the Exero Technologies company.

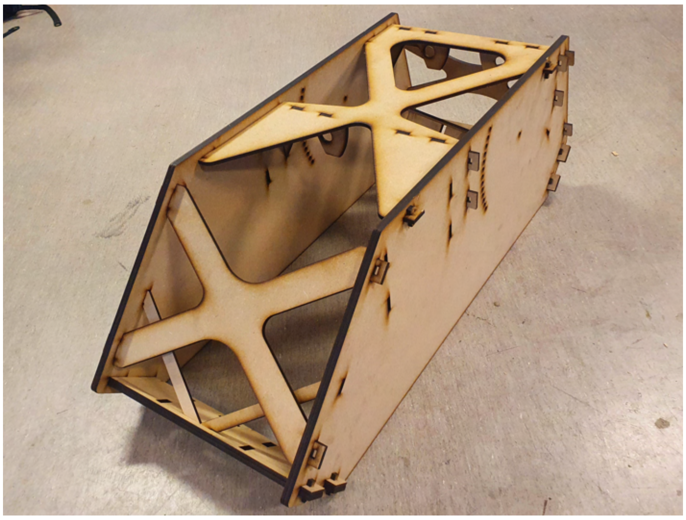


Figure 51: Test rig in laser cut MDF without motor, suspension, steering modules or seat mounted.

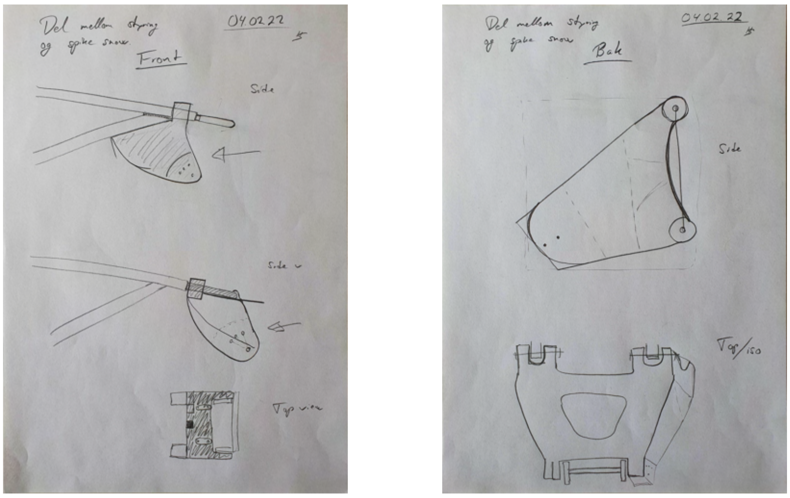
5 Design and construction of parts and mechanisms to integrate motor and turning on the Exero Spike Snow

The work of integrating steering and motor on the Exero Spike Snow began by first constructing modules at the front and rear to test if the cross-country sit-ski could easily be modified to enable steering. The Exero Spike Snow frame, Figure 52, was kindly supplied by Exero Technologies and was used as the basis frame for the additional parts. After successful testing of the steering modules, a motor and belt module was integrated and mounted on the frame with suspension and height adjustment mechanisms. This process is described more in detail in the following sub-chapters.

Figure 52: Exero Spike Snow frame in lab without additional parts.

5.1 Construction and testing of steering modules on Spike Snow

Initially, steering modules were designed and mounted on the Spike Snow to accommodate turning and then tested to verify their function and use before other modules were designed and integrated. With the steering module configuration already designed and constructed for the test rig, the same configuration with adjustable angling was used. Figure 53 shows the proposed designs for steering modules, front and rear. The modules were designed to maintain the same angle of the cross-country sit-ski in relation to the ground, meaning that the sit-ski would only be lifted a couple of centimetres above the ground. Figure 53a shows two proposed ideas for how to mount the front steering module on the frame. The top shows the module mounted on the frame and the bottom shows the module mounted on the foot-rest, which is adjustable. Because the top module could potentially restrict the placement of the suspension and motor, the bottom configuration was constructed.



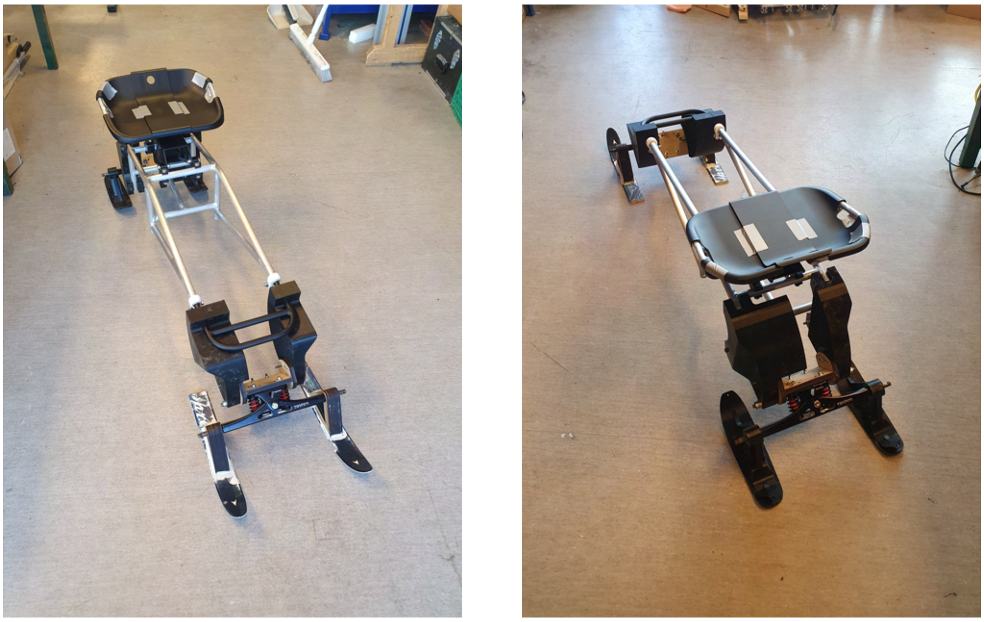
(a) Sketch of front steering module for Spike Snow.

(b) Sketch of rear steering module for Spike Snow.

Figure 53: Sketch of steering modules for Spike Snow.

From the designs shown in the sketches above, CAD-models were created and parts manufactured in PLA using additive manufacturing. The parts were divided in two to enable the 3D printing on Original Prusa i3 printers. Several of the prints failed during print, but could still be mounted on the Spike Snow frame and tested. Figure 54 shows the frame with steering modules (black), angle adjustment plate in MDF and steering trucks with skis.

Because the front steering module was mounted on the foot-rest, a bending moment was created in the aluminium tube connecting the foot-rest to the frame. This resulted in bending of the tube and limited how far the foot-rest could be pulled out. If pulled too far out, the tube would bend because of the load of the user, potentially leading to a permanently bent tube or worse, fracture. For this reason the foot-rest was pushed as far in as possible to limit the bending in the tube.



(a) Exero Spike Snow frame with steering modules, front view.

(b) Exero Spike Snow frame with steering modules, rear view.

Figure 54: Exero Spike Snow frame with simple steering modules in Lab.

To find out if and how the steering modules enabled sufficient turning of the Exero Spike Snow, a simple test was performed on snow. Through this test potential weaknesses of the design could also be discovered. The cross-country sit-ski was tested on and around a parking lot and up and down a small hill, roughly 5 degrees inclination. The ground was covered in snow but had been shovelled so the ground base was hard with a little powder snow on top. The test was performed sitting in the normal position and double poling. Turning was achieved by leaning the upper body to the side one wanted to turn to. Figure 55a shows a user double poling. Through testing, the steering modules proved to work well for steering and allowed the user to steer the Spike Snow while double poling, both on flat ground and up and down hill. Figure 55b shows how the steering worked when the user leaned to the right. Due to the dynamics of the steering trucks system, the skis turn, in this case to the left. The front trucks do the same as the rear, but turn the skis in the opposite direction. This allows the user to easily steer, simply by leaning to the side. It was not possible to do very sharp turns due to the stiffness of the dampers (red colour) used in the trucks, but it is possible to replace these by softer ones that will enable easier and sharper turning [31]. This is because the trucks will be less restricted by the damper, resulting in more turning of the skis.

(a) User double poling on flat ground.

(b) Rear view, tilt to the right.

Figure 55: Exero Spike Snow with steering modules tested outside.

Due to the failed 3D-prints of the front and rear steering modules the trucks were not mounted exactly as designed, but slightly skewed. As a result of this, the front skis turned slightly to the right when the user sat in a neutral position. To correct this, new front steering modules were printed and mounted, Figure 56.

Figure 56: New front steering module on the Exero Spike Snow frame.

5.2 Construction of suspension system for motor and motor housing

After the steering modules were verified to function as intended, motor and suspension modules were integrated into the frame. The motor was the same as the one that was used in the specialisation project, described in Section 3.1.7. First, exploration into how and if the motor and belt would fit inside the frame were performed. In order to fit the motor and belt inside the Spike Snow frame, two of the frame tube members had to be removed. Figure 57 shows the frame before and after removal of the two tube members to fit the motor and belt inside. After removing the two frame members, the chassis became a lot weaker. A bending moment was created when sitting on the chassis after the frame members were removed because of the momentum arm created as a result of the vertical force from the ground to the rear ski. This bending moment threatened to bend or fracture the chassis at the corner between the top and rear tube members of the frame. To prevent this, the chassis had to be reinforced somehow. Figure 57a shows how clamps could be used to reinforce the chassis. This showed that the chassis could be reinforced with clamps, but was highly impractical as the clamps took up too much space. Figure 57b shows another proposed idea, the use of a strap to reinforce the frame. This was more promising than the clamps because the strap took up less space, but the strap did however restrict the movement of the motor axle. Therefore a better solution had to be designed, but this was designed after the suspension design and height adjustment mechanism had been designed and tested to work as intended.

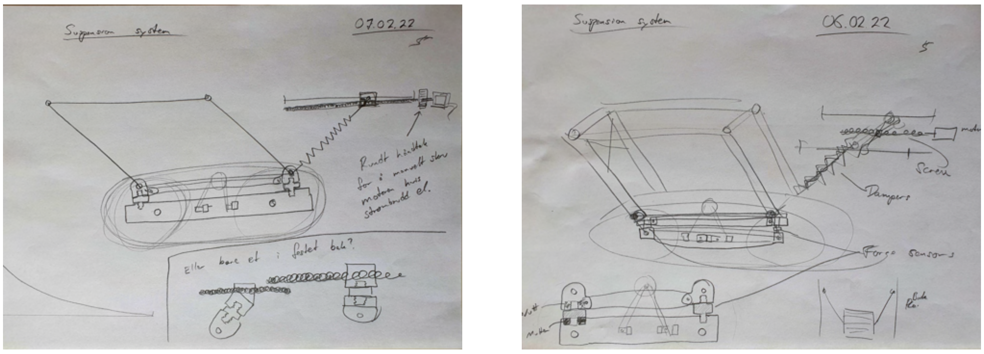
(a) Frame before removal of the two tube members.

(b) Frame with motor and belt inside frame after two tube members were removed.

Figure 57: Exero Spike Snow frame with clamps and straps to reinforce frame after removal of two frame tube members to make room for motor and belt module.

5.2.1 Design of suspension system

A suspension configuration was designed to connect the motor and belt module to the chassis. Due to the limited space available the design possibilities were restricted. The only viable suspension design that seemed easy to integrate was a design configuration similar to the one presented in Figure 45a in Section 4.2. Figure 58 shows two sketches of the suspension configuration. Four link members connect the motor and belt to the chassis and two spring members connect the motor and belt module to a height adjustment mechanism. With the spring suspension mounted at the rear, the motor and belt module will dig into the ground when the motor turns the belt to go forward due to the geometry of the suspension. The height adjustment mechanism is explained more in detail in Section 5.3.



(a) Sketch of suspension design side view, 2D.

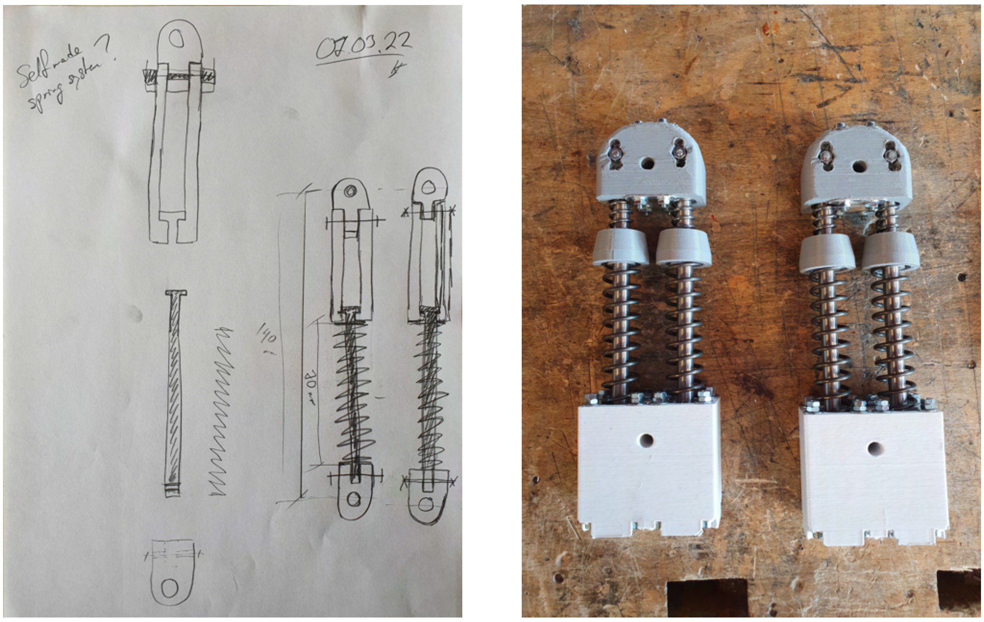
(b) Sketch of suspension design, 3D.

Figure 58: Sketch of suspension design to integrate motor and belt module in Exero Spike Snow frame.

5.2.2 Design of spring suspension system

A spring design was developed based on the dimensions of the available space in the Exero Spike Snow frame. First, available off-the-shelf springs and dampers were investigated, but none were found to fit the desired specifications of length, spring travel and spring coefficient. It was therefore decided to design a spring system that could meet the requirements. Figure 59a shows a sketch of a proposed spring design. This spring configuration, with mounting holes on either side, was however difficult to design to accommodate short distances between mounting holes and also enable relatively long spring travel. To solve this challenge, a new double piston spring suspension with mounting holes closer to each other was designed. Figure 59b shows the two spring suspension systems constructed. The grey and white parts are produced in 3D printed PLA, high infill.

The piston rods, stainless steel, are mounted to the top grey part through M3 bolts. The spring suspension has a pre-load of 10 mm, equal to 4.63 kg per system. To connect the white part, a short splint through the rods (visible in Figure 61b) keeps the system pre-loaded when not loaded. Due to difficulties in finding coil springs with the right spring coefficient and dimensions, two different springs were used per piston. The larger spring has a coefficient of 3.19 N/mm and the smallest spring has a coefficient of 7.87 N/mm. Combining these results in a combined spring coefficient per piston of 2.27 N/mm and per system of 4.54 N/mm. The distance between the mounting holes is 125 mm and the maximum spring travel is 75mm. At maximum compression, each system is loaded with 385.9 N, equating to 39.3 kg, and two systems are then loaded with 78.6 kg at maximum compression. To reduce the risk of fracture, the PLA parts were reinforced with M3 bolts and nuts. A fracture could cancel testing and potentially break more parts. The added time spent to reinforce the system to reduce the risk of fracture and the added weight of the bolts was considered worth it.



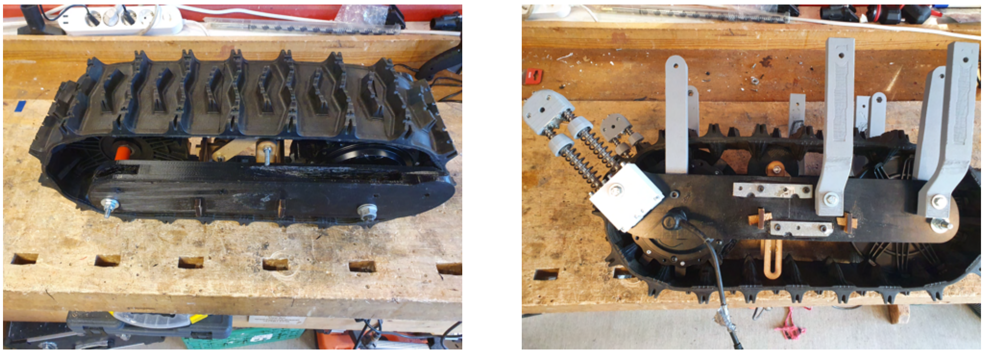
(a) Sketch of proposed spring suspension design.

(b) The spring systems constructed.

Figure 59: Spring suspension system development.

5.2.3 Motor housing and suspension mount on chassis

The MDF-side plates on the motor housing from the previous wooden prototype were replaced by stronger ABS and PLA 3D-printed parts. By using a stronger material the drive axle would hopefully be held in place and not turn around like it did in the wooden prototype created in the specialisation project [23]. One side was printed in ABS in one single part before the large printer used for this stopped working. The other side was printed in two pieces in PLA on smaller printers and glued and reinforced with small steel plates on either side. Figure 60a shows the side plate printed in ABS and in Figure 60b the side plate in PLA with steel reinforcement is shown. To increase the stiffness of the suspension and reduce rotation around y axis and reduce movement along z axis, extra link members were added. These are the outer grey members seen in Figure 60b.

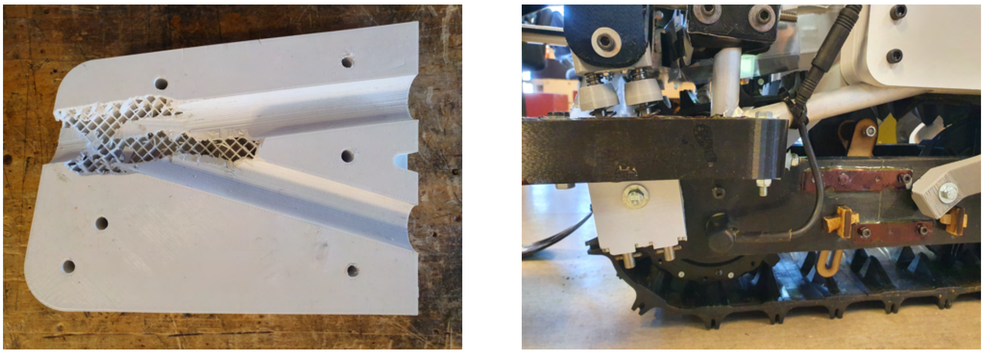


(a) Motor housing left side without suspension members.

(b) Motor housing right side with suspension members.

Figure 60: Motor housing with suspension link members and spring system.

To mount the suspension on the Exero Spike Snow, brackets were designed and manufactured. The suspension brackets were designed using CAD-software to be manufactured in one part using 3D printing. However, due to issues with the intended 3D-printer, the parts had to be divided in two and printed on separate printers. Figure 61a shows one of the 3D-printed parts with post-print improvements to fit on the frame. There was a slight geometrical difference between the actual frame and the CAD-frame used to design the suspension brackets. Slight adjustments to the parts, such as removal of material, were made to fit them on the frame. Figure 61b shows the suspension mounted on the cross-country sit-ski in lowered position. The suspension brackets, white, mounted on the chassis can be seen.



(a) Suspension mounting bracket with fixes.

(b) Suspension mounted and lowered on sit-ski.

Figure 61: Suspension mounting bracket and suspension mounted on chassis.

5.3 Construction of height adjustment mechanism

To adjust the height of the belt and ground pressure, a height adjustment mechanism was designed and constructed. It was important to be able to lift the belt above the ground in case the motor malfunctioned or the battery was empty. Then the prototype could instead be dragged or pulled back to the starting position. Because the motor was designed such that backward drive was not possible, lifting the belt above the ground would also be necessary to reverse the cross-country sit-ski. Furthermore, to be able to adjust the suspension load and the belt-to-ground pressure, the height adjustment mechanism would have to be strong enough to increase and decrease the load to the desired amount. By increasing and decreasing the belt-to-ground pressure during testing on different snow types and in different inclinations, the best and worst settings and configurations could be found. This could further be used to improve the suspension and height adjustment mechanism to achieve the best possible traction and function. The design and construction of the height adjustment mechanism is explained further in this subsection.

5.3.1 Height adjustment mechanism design

The design of the height adjustment mechanism was largely determined by the geometry and space available on the prototype, but also by the previous work conducted in the specialisation project. In the specialisation project several possible designs for a height adjustment mechanism were investigated, ranging from manual pivot and sliding mechanisms to motor driven screw mechanisms, Section 3.1.8 [23]. The chosen design evolved from the height adjustment mechanism used on the wooden prototype, but was changed to incorporate the spring system chosen and to fit inside the limited space available on the Exero Spike Snow. Figure 62 shows a sketch of the proposed design. At the top, the mechanism is sketched in top view with the rear side being closest to the bottom of the page. The spring system on the suspension is connected to a slider that is mounted on a tube and can slide back and forth. The slider is connected to a nut on a threaded rod which is driven by a motor. By turning the rod, the slider is moved back or forth. This screw mechanism is drawn in more detail at the bottom of the sketch.

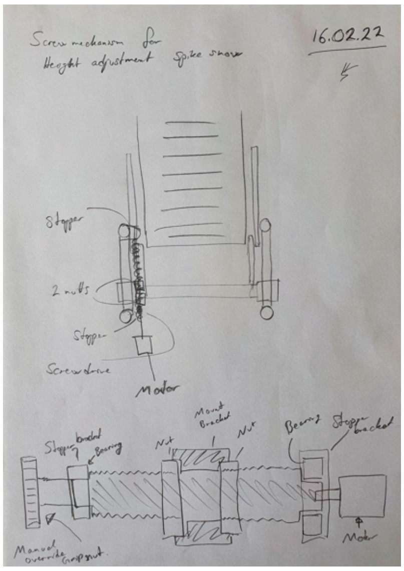


Figure 62: Sketch of the proposed height adjustment mechanism with top view and detailed view of the screw mechanism.

The proposed design from the sketch in Figure 62 was further developed to be integrated into the Spike Snow. Figure 63 shows several sketches of the design before it was integrated into the CAD-model. In particular, the parts that would be mounted on the frame to support the height adjustment mechanism are drawn, with bearings and bolt holes, motor, Arduino, battery and nuts to secure the threaded rod visualised. Two motors, one per threaded drive rod, were chosen because of the difficulty of integrating only one due to space limitations. With only one motor in the middle, driving both sliders, the drive rod would be in the way for the belt in lifted position. In addition, one motor would have to be twice as powerful as two motors to be able to produce the same force or torque required to move the sliders. On the other hand, two motors would have to be in synchrony, rotating at the same RPM to avoid uneven drive and skewed geometry. To avoid the motors coming out of synchrony, as a result of, for instance, uneven load, a link member connecting the two sliders was proposed. This link is sketched in Figure 63, but was neither integrated in the CAD-model, nor created physically because it saved time and was evaluated as unnecessary to complete the planned testing.

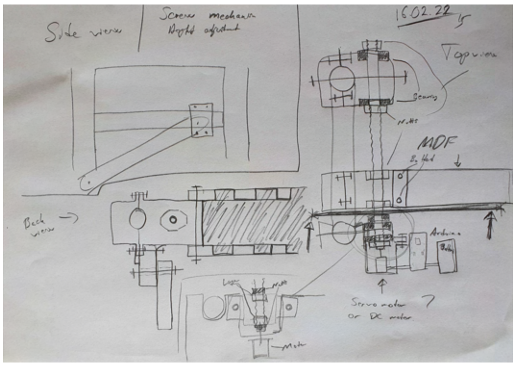
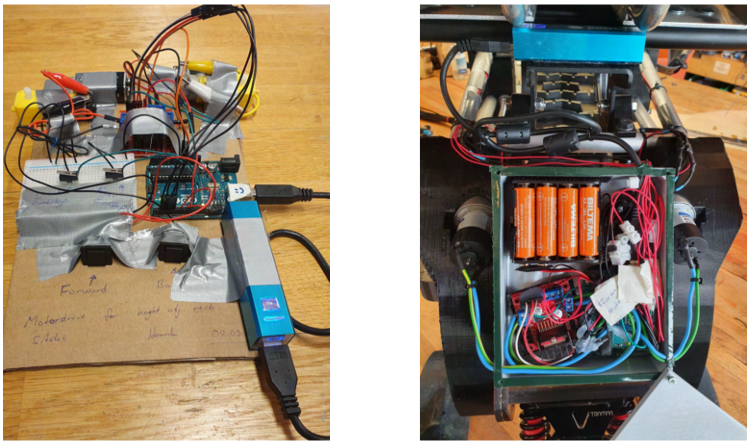


Figure 63: Sketches of the height adjustment mechanism in higher resolution, with parts such as nuts, bolts and bearings visualised.

5.3.2 Electronics

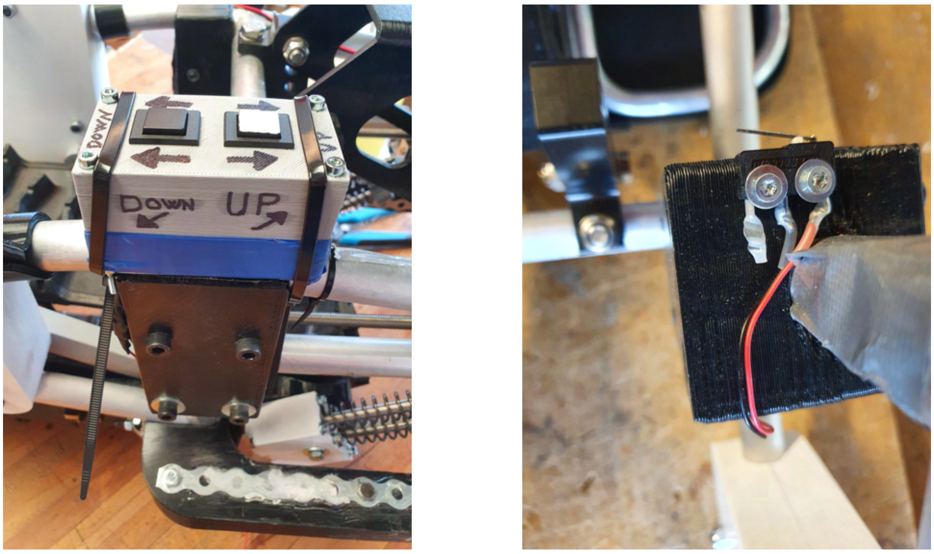
The height adjustment mechanism was designed to be driven by two DC electric motors and operated by buttons. A simple prototype of the electronics was constructed to make sure the system would function as intended, with buttons and code working. Figure 64a shows the simple electronics prototype. It consisted of an Arduino UNO (green), Power bank (blue), two DC motors (yellow), one L298N Motor Driver (red), two push buttons (black), one 9V battery, two end stopper buttons on a breadboard and wires. A code was written to enable drive of the motors through the Arduino when the push buttons were pushed. One for clockwise and one for counterclockwise rotation of the motors. If both buttons were pressed, nothing happened. If the end stoppers were pressed, the motors would reverse direction until they were released again. After successful testing of the simple prototype, the electronics were integrated into the Spike Snow prototype. A box was 3D-printed to house the electronics, such as battery, Arduino and motor driver. The power bank was placed outside the box to allow for easy charging and access. The system was turned on and off by connecting and disconnecting the USB-cable to the power bank respectively. The motors used in the final system were RH158-12-250 Geared DC motors with the following characteristics: 12 V, 8 W, 21 RPM, 1 Nm torque [18]. The motors were specifically chosen for their high torque to make sure they could turn the threaded rods under load, while the speed was not important for the system to work. Speed was then sacrificed to save weight with a lighter and less powerful motor. 8 AA batteries were used to supply power to drive the motors, while the Arduino was driven by the 5V power bank. Figure 64b shows the electronics integrated on the final sit-ski prototype with the electronics box lid off. See Appendix A for the circuit diagram and Appendix B Arduino code.



(a) Prototype of electronics.

(b) Electronics box with motors on the side.

Figure 64: Electronics prototype and box with electronics integrated on the cross-country sit-ski prototype.



(a) Button box for operation.

(b) Front end stopper.

Figure 65: Button box for operation of height adjustment and end stopper for the height adjustment mechanism.

The two buttons that are used to operate the height adjustment mechanism were integrated into a button box which was mounted on the side of the cross-country sit-ski prototype. Figure 65a shows the button box mounted on the sit-ski. The button box was attached to the sit-ski with Velcro tape and strips to keep it in place during use. Figure 65b shows the end stopper mounted on the front bracket of the height adjustment mechanism. When the DOWN button is pressed, the two DC motors turn the threaded rods, which then move the sliders (black) forward on the aluminium tubes. This moves the connection point of the suspension forward, thereby lowering the motor and belt module or increasing the load on the spring suspension. Figure 66 shows the whole mechanism from the side. If the sliders reach the black height adjustment bracket, the end stoppers are pressed. This reverses the DC motors, moving the sliders backward until the front end stoppers are no longer pressed. The same happens when the UP button is pressed, the slider moves backward, lifting the motor and belt module or reducing the load on the spring suspension. If the sliders reach the rear height adjustment bracket, the rear end stoppers will be engaged, thereby reversing the DC motors until the rear end stoppers are no longer pressed. The DC motors only move while the buttons are pressed.

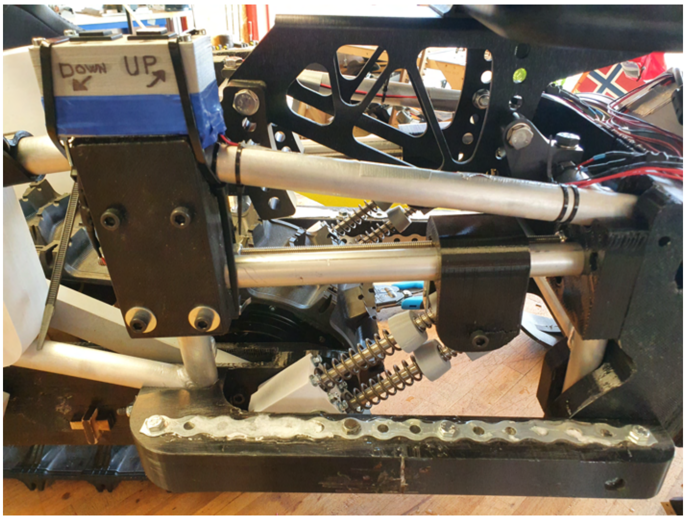
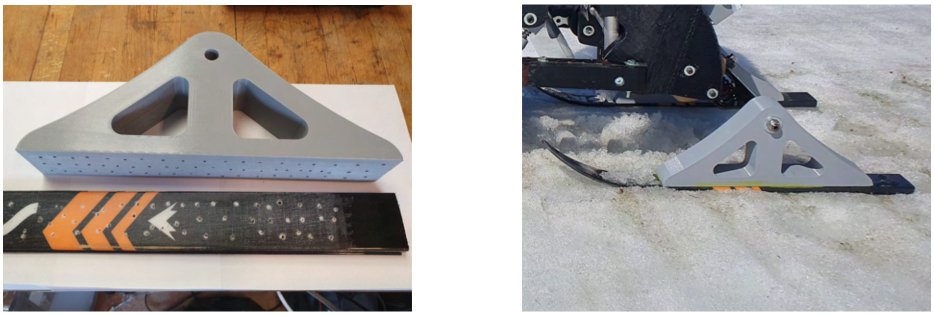


Figure 66: Height adjustment mechanism, view from left side.

5.4 Design and construction of skis using additive manufactured

New straighter and longer skis were designed to improve the sit-ski compared to the wooden prototype. Longer skis would allow the skis to more easily stay on top of several types of snow. Two of the skis used on the wood prototype in the specialisation project were slightly skewed [23]. By making straighter skis, the sit-ski would not turn to one side because of the skis, but rather the turning mechanism, reducing the sources of error in the planned testing phase. Figure 67 shows the ski designed in CAD-software intended to be 3D-printed. Due to issues with the only available printer large enough to print the skis, the skis were simplified and constructed using the front part of children skis and bindings printed on smaller 3D-printers. Figure 68 shows the two parts before glueing and how the ski is mounted on the sit-ski.

Figure 67: Ski designed in CAD to be 3D-printed.



(a) Children ski and binding with drilled holes before glueing.

(b) Ski mounted on sit-ski.

Figure 68: Ski manufactured using the front part of a children's ski and a 3D-printed binding.

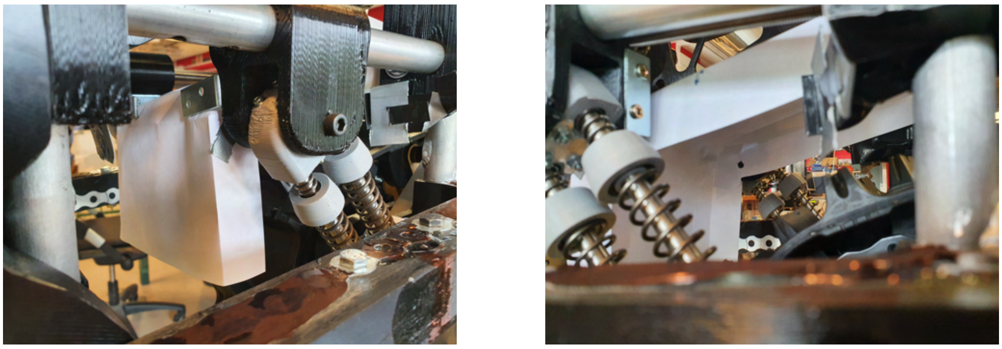
5.5 Snow and water precautions

To protect the electronics from water and snow, components were covered with tape and a plastic splash shield was mounted round the belt to limit snow spray. In particular, the end stoppers were exposed such that they needed extra protection. Figure 69 shows the front end stopper on the right side of the prototype before and after applying tape as protection. The added tape on the end stoppers increased their thickness of around 3 mm. This resulted in a total reduction of sliding movement for the height adjustment mechanism of about 6 mm. This reduced the maximum possible height of the belt above the ground to 15 to 20 mm from 25 to 30 mm, depending on how much belt tension was applied. However, it did not result in any measurable difference in maximum ground pressure in the lowest position due to the geometry of the suspension and height adjustment mechanism.

(a) End stopper before tape as protection. (b) End stopper covered in tape as protection.

Figure 69: Front end stopper on right side before and after tape protection.

To construct the plastic snow spray shield around the belt track, A4-paper was used to find the necessary and possible geometry. This is shown in Figure 70. See-through laminating pouches were temperature treated with no paper inside to create tough plastic sheets. These were then bent and adjusted to fit around the belt. The rear shield was mounted on the height adjustment sliding mechanism seen in Figure 70a. Other sheets were mounted under the battery to avoid snow spray on the feet of the user. Care was taken when mounting the sheets to ensure proper overlap and smooth contact between the movable sheet mounted on the sliding mechanism and the fixed sheets mounted under the battery. Video and pictures from testing found in Section 6 show the snow spray shield in operation.



(a) Rear side view from right. (b) Front side view from right.

Figure 70: The A4-paper used to develop the shape of the snow spray shield.

5.6 Control, safety and battery placement

The motor was controlled with a thumb throttle, similar to the one used in the specialisation project. Some improvements and adjustments were done compared to the wooden prototype. Firstly, the cable between the battery and thumb throttle on the ski pole was held in place close to the body with the use of two straps, Figure 71a. This ensured that the cable did not get entangled or unintentionally pulled. Secondly, the thumb throttle was placed on the ski pole such that it was operated using the index finger instead of the thumb. Figure 71b shows the thumb throttle mounted on the ski pole before tape was used to properly secure the 3D printed grey part. The grey part was constructed to keep the thumb throttle intact, hindering the actual finger throttle from falling off. Thirdly, the thumb throttle mechanism has a spring, in contrast to the one used with the wooden prototype. If the user lets go of the ski pole or takes the finger off the thumb throttle, the main belt motor stops because the thumb throttle snaps back in neutral.

(a) User with straps for cable.

(b) Thumb throttle on ski pole.

Figure 71: User with the straps around upper body to keep cable in place and thumb throttle before tape was added.

In addition to the thumb throttle, the control panel and screen were also mounted on the ski pole. This enabled easy control of the motor, with the ON and OFF buttons and the info screen placed on top of the ski pole. Figure 72a shows the thumb throttle operated with the index finger. The info screen is shown with an arrow in Figure 72b. The red line shows the position of the cable. The thick line close to the battery represents the connection where the cable and battery connect. This connection provides a safety mechanism should there be any difficulty with the thumb throttle. If the circuit is broken, the motor stops. If the user pulls the cable, the cable is disconnected at the connection and the motor stops. This cable connection is located between the legs of the user, enabling easy access to the cable. Furthermore, the battery is placed under the feet for two reasons. Firstly, by placing the battery further towards the front of the prototype more weight would be distributed on the front skis. More weight on the front skis would result in more pressure on the ground resulting in better steering effect of the skis when turning. Because most of the weight was distributed on the rear skis, placing the battery towards the front greatly improved the weight distribution. Secondly, the cable between the battery and the thumb throttle had a limited length, meaning that the battery had to be placed somewhere not too far from the hips of the user for the cable to reach all the way to the thumb throttle.

(a) Index finger on the thumb throttle.

(b) Cable from thumb throttle to battery.

Figure 72: Thumb throttle on ski pole with cables and user.

5.7 Final prototype construction

The final prototype construction is presented in this subsection with pictures and information such as dimensions and weight. Figure 74 presents renders of the cross-country sit-ski CAD-model. The left figure presents the whole prototype in ISO view and the right figure presents a cross sectional view of the prototype where the inside of the motor and belt module is visible. Key dimensions are presented in mm in Figure 75. The dimensions from the CAD model match the dimensions on the physical prototype. The user was measured to sit 45 cm above the ground without the pillow and 48 cm above the ground with the pillow. The prototype weighed 31.5 kg with battery, of which only the battery, electric motor and Exero Spike Snow frame weighed in at circa 12 kg combined. With a test user, 60 kg and 178 cm tall, sitting on the prototype with a straight back in a normal position, the weight distribution was measured to be: 35% weight on the front skis and 65% on the rear skis. Without a user, the weight distribution was measured to be: 45% on the front skis and 55% on the rear skis. Figure 76, 77 and 78 show the final prototype in the ski track with and without a user on the day of testing. The Arduino code and circuit diagram of the electronics can be found in Appendix B and Appendix A respectively.

Link to folder with CAD-files:

https://drive.google.com/drive/folders/1Td5RDoymENTyBoMiNjMd2K6NrMBSluYk

Link to video of height adjustment mechanism:

https://drive.google.com/drive/folders/1IocBRiYVHhTH6BD-pFolRz7nAJ0cczow

(a) QR-code, CAD files folder. (b) QR-code, height adjustment.

Figure 73: QR-codes to CAD-files folder and video of height adjustment mechanism in operation in LAB.

(a) Render or CAD-model. (b) Render of CAD-model cross sectional view.

Figure 74: Renders of CAD-model without seat.

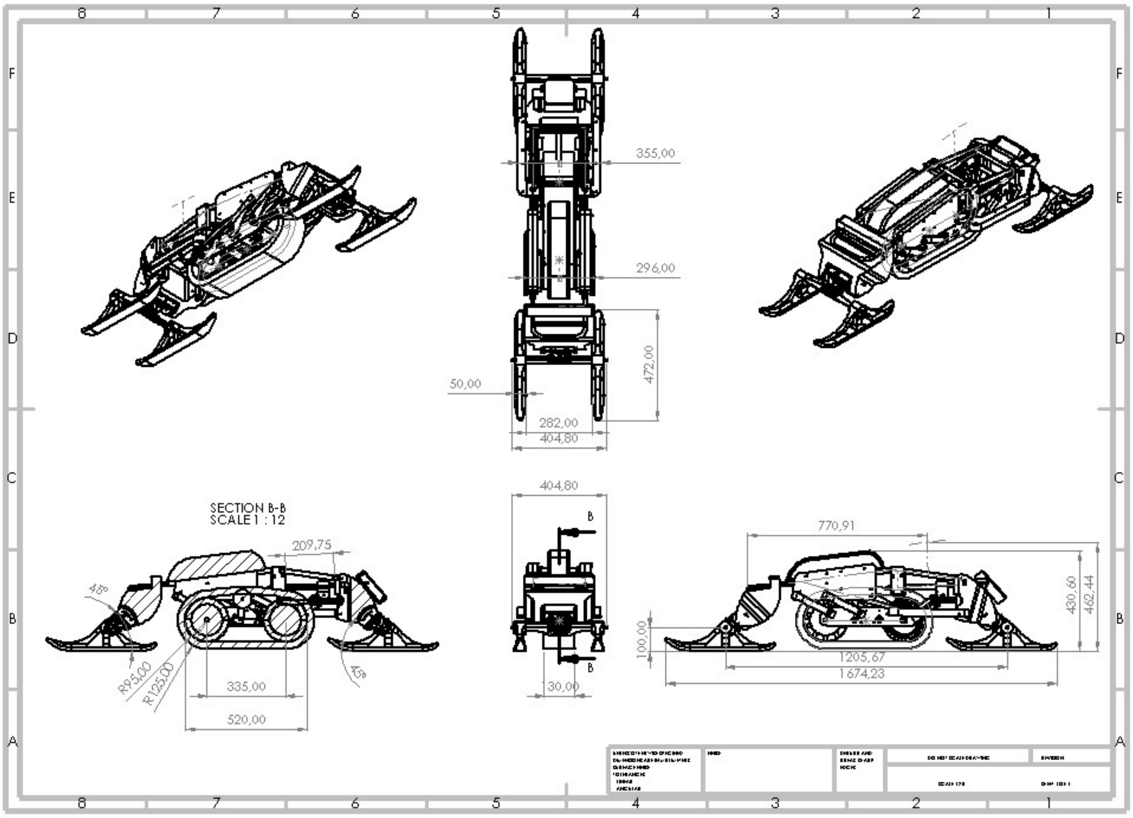


Figure 75: Engineering drawing of final prototype with dimensions.

Figure 76: Final prototype in ski track, side view.

(a) Prototype with user, right view.

(b) Prototype with user, left view.

Figure 77: Final prototype in ski track with user.

Figure 78: Final prototype with user in ski track, rear view.

6 Prototype testing and results from testing

The cross-country sit-ski prototype was tested in a ski track in Storlidalen in Norway to sample both qualitative and quantitative results. Because of construction delays due to issues with a 3D-printer, the testing was not conducted before the 7th of June, resulting in limited ski tracks and snow available for testing. Valuable data was however gathered and vital information about what worked and what should be improved on the cross-country sit-ski prototype was identified.

In addition to the testing conducted in the ski track, measurements of individual mechanisms were taken in a controlled environment in a laboratory. The height adjustment mechanism was tested to measure the spring compression and spring load at different settings. The maximum turning angles at different settings of the steering mechanism were also measured because the ski track used for the main testing was not wide enough to measure the turning radius at different settings.

6.1 Qualitative results

The Exero Spike Snow and the prototype were tested thoroughly by three test participants to explore performance, how they compared and what might be improved on the prototype. Both sit-skis were tested in the same snow track with the same weather, snow and trail characteristics. Both were tested in sections such as flat ground, small uphill, small downhill and turning. The seats on both sit-skis were set to the same height setting to make the sitting positions as similar as possible. Furthermore, the foot rests were placed such that the sitting position would be as similar as possible, without compromising comfort. The testing with participant number 1 was the most thorough because he was an experienced user of cross-country sit-skis and had Cerebral Palsy. This meant that the most valuable findings would likely come from him because he would more easily highlight and identify the real user needs. The two other test participants had little to no experience with cross-country sit-skiing, but had good experience with regular cross-country skiing and had no disabilities. This meant that the prototype might work well for participant 2 and 3, while not discovering how the prototype would function for intended users or explore and identify aspects that should be improved to better meet the user needs.

6.1.1 Testing and findings with participant 1

The first test participant tested the Exero Spike Snow first, and then the prototype afterwards. Test participant number 1 had Cerebral Palsy, between level 2 and 3, depending on how it is measured [33], with good strength in the upper body. He was able to walk and move around easily with a wheelchair.

Information about test participant 1:
Weight: 55 kg
Height: 185 cm
Years of experience with cross-country sit-skiing.
Never tried the Exero Spike Snow before.

"It is difficult to regulate the speed and brake effectively."

Comment from participant 1 after testing in downhill section with Exero Spike Snow.

Testing Exero Spike Snow

Section: Flat ground.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.

First, the test participant tried the sit-ski on flat ground, double poling to move around. Figure 79 shows the participant sitting on the Exero Spike Snow. The user easily double poled along the flat section. The participant looked comfortable and happy moving forward. On questions about the comfort, the user replied that it was comfortable to use and that he liked that the Spike seat did not have a supported back. Because the ski track ground tilted slightly to the right, the participant had to turn to the left to avoid ending up in the trench beside the track. The user said he was happy he managed to turn so easily to avoid ending up in the trench. On questions about the stability, the user commented that the sit-ski was a good and stable sit-ski. When asked about other comments about the experience, he answered: *"Okay. Double poling goes well. This is one of the better cross-country sit-skis that are not for sitting on the knees. It is difficult to get proper grip with the ski poles, but this is because of the snow conditions."* The ski track sole was icy and hard, making it difficult to get proper grip.

Figure 79: Test participant 1 sitting on the Exero Spike Snow double poling on the flat section.

Section: Small uphill, 4°.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.

The next test was to double pole up a small hill of 4°, 40-45 metres long. At one point in the hill the sit-ski slid a bit sideways because of a tilt in the snow track. However, the test participant managed to bring himself back on the track again, avoiding falling over in the trench. The test participant commented that the stability was good and that it was easy to turn the sit-ski back again when he slid out to the side. Regarding comfort, he commented that the seat was very good, and that the ergonomics of the seat and sit-ski made it comfortable to go uphill. However, it was extremely tiring and the participant pointed out that he was not able to take a break when he wanted to because he would then slide back down. The test participant found the hill to be tiring to climb. Furthermore, the participant commented the following about the experience: *"Okay uphill-section. The sit-ski is comfortable and provides a good sitting position for uphill double pulling. However, all work is done manually, and it is tiring. The technique; forward leaning, fast and short double poling is a bit challenging."*

SECTION: TURNING.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.

At the top of the hill the test participant tested turning with as sharp turns as possible. Figure 80 shows two pictures of turns, one of a right turn and one of a left turn. The right turn had a turning radius of about 5 to 6 metres +/- 1 metre, and the left turn had a turning radius of about 4 metres +/-1 metre. The turning was performed by leaning the knees to the side the participant wanted to turn to and then poling with extra force through the outer ski pole to turn. To create an extra sharp turn, the inside ski pole can be used to push backwards. This technique can be seen in Figure 80.

(a) Right turn.

(b) Left turn.

Figure 80: Turning with the Exero Spike Snow by test participant 1.

Afterwards, the test participant tried to do a 180°turn, but this was difficult and required a lot of going back and forth. It was particularly difficult because the side of the skis dug down into the snow. The user said that the stability was good and that he was not afraid to fall over while turning and the comfort was overall good. He also mentioned that the knee straps on the Spike Snow were a bit in the way when reversing. This might be avoided by adjusting the straps better or lowering the knees further.

SECTION: SMALL DOWNHILL, 4°.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.

> *"Downhills are intimidating."*
>
> Comment from participant 1 after testing in downhill section with Exero Spike Snow.

Finally, the first participant tested the Exero Spike Snow downhill. A strap was mounted on the rear of the sit-ski so that the person walking behind could stop the sit-ski if necessary. This was also of great reassurance to the test participant because he knew that the person behind could stop him, should he feel uncomfortable or lose control. The participant started out slowly and found it difficult to turn and as a result he ended up on the side of the ski track. He then had to go back a little to turn the Spike Snow in the right direction again. After this he moved down the slope again. At the bottom of the hill, he was about to go into the trench on the side of the track, but managed to turn slightly to the right thereby avoiding the trench. Afterwards, the participant said that the turning at the bottom felt easy. The stability was also good and it was not easy to tilt the sit-ski. However, he said that it was difficult to control when going fast downhill. When asked about the comfort the participant said the following: *"Downhill is scary. It is difficult to regulate the speed and break effectively. Downhills are intimidating."* The participant also said he normally is afraid of falling when going downhill because he feels he has too little control of the speed. Therefore, he usually tries to avoid downhills. The person walking behind helped with braking on two occasions and the participant found all speeds above roughly 6 km/h to be uncomfortable because he then felt that he lost control over the sit-ski.

Link to video of downhill section:

https://drive.google.com/drive/folders/1vhPaXnoeyqz4cZ-hSi55bOqQee6_bea5

Figure 81: QR-code for link to video of participant 1 testing the Spike Snow downhill.

Testing developed prototype

"I am almost out of words!"

Comment from participant 1 when testing the prototype.

Participant 1 then tested the prototype in the same scenarios as the Spike Snow; flat ground, small uphill, turning and small downhill. The participant managed to get in and out of the prototype on his own, with only some supports to hold on to. This is more difficult on other cross-country sit-skis. It seemed easier to sit down in the prototype because the seat was a little higher and the belt worked as a brake, avoiding the sit-ski sliding away. The steering modules were set to 45° and the sitting position was set to be as similar to the Spike Snow as possible. Figure 82 shows the prototype with the first participant sitting in the prototype with the belt lowered. A strap (blue) was used over the feet to hold them in position, as they otherwise easily fell out to the side during movements. Before the participant turned on the motor, he tested whether he managed to pull out the cable connected between the battery and the ski pole. With a light jerk with his left hand, this was easily achieved. This provided the participant with an extra feeling of safety. Figure 104 explains how the slider distance was measured.

(a) Side view of strap used around feet.

(b) Side view with belt lowered.

Figure 82: Setup of the prototype for testing.

Section: Flat ground.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.
Steering module angle: 45°
Slider distance: 80 mm
Spring load (neutral position): 10.2 kg

First, the prototype was tested on a flat section of the ski track. The belt was lowered to give a spring load of 10.2 kg. The participant double poled along the flat section and operated the throttle with his right index finger. In the beginning he struggled to maintain a constant pressure on the throttle. This resulted in uneven motion because the motor gave uneven thrust. After about 10 metres with this jerky motion the participant managed to maintain an even force on the throttle while double poling. Later he even managed to fine tune the speed by applying more or less force on the throttle. The user commented that the prototype was very stable and that he was not afraid to fall over. Furthermore, he said that the height of the ski poles was very good and that it made sense to control the motor throttle with the hand. He added: *"Good to sit in. I sit a little higher, good overview, very nice."* When he managed to maintain even motor propulsion, he commented that the belt worked well. The belt then spun a little because of some deeper snow, but with a little more thrust through the ski poles and more power with the motor, the participant managed to move over the deeper snow. Because of a small tilt to the right in the track, the participant had to lean to the left to move straight and not into the trench on the right. He said it would help to train more on turning to get more used to it. It was a little unnatural to lean the upper body so much to the side to be able to turn.

Link to videos of the prototype tested on flat ground with participant 1:

https://drive.google.com/drive/folders/1JGO1K-xzxC6UfK1xLAktvt9hO5k489Ns

https://drive.google.com/drive/folders/13m2Yervj7a1dG8_cxpc5j-VkYj09ZFky

(a) QR-code, flat ground.

(b) QR-code, side view belt.

Figure 83: QR-codes to videos of participant 1 testing the prototype on flat ground.

Section: Small uphill, 4°.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.
Steering module angle: 45°
Slider distance: (1) 80 mm, (2) 110 mm, (3) 130 mm
Spring load (neutral position): (1) 10.2 kg, (2) 22.2 kg, (3) 28.7 kg

"It stops in the uphill! Wonderful!"

Comment from participant 1 when testing the prototype uphill.

At the start of the small 4° uphill of 40-45 metres, the slider distance was left at 80 mm. This provided good traction up the hill, with little need to use more force when double poling. Participant 1 said that the prototype still felt stable and comfortable. About half way up, the belt started to spin and lost traction because of deeper and looser snow. The participant did not manage to get further up the hill, but could take a break because the belt worked as a brake. The belt was lowered further by moving the slider to a distance of 110 mm. This increased the spring load to 22.2 kg. Because the belt had dug down into the snow and created a pit, the belt still spun and the prototype was still stuck. The slider was then moved to 130 mm, increasing the spring load to 28.7 kg. With this setting, the participant got traction with the belt and managed to get past the pit. Figure 84 shows the user lowering the belt. Figure 85 shows the measurement of the pit and the trail left behind the prototype past the pit up the hill. The participant continued up the hill with ease. At the top he was asked about the experience, and he exclaimed: *"It stops in the uphill! Wonderful!"* He further explained that he normally finds it difficult to go uphill as he has to maintain a very high double poling pace to avoid sliding back down between each repetition. This high pace technique is difficult and very exhausting regardless of whether he has to take a break uphill. It is also very strenuous to start moving up the hill again if he needs a break in the hill. With the belt acting as a brake in the hill, he could take a break and relax if he needed to, without sliding back down. This is a huge problem for him and he was therefore extremely happy about the braking effect when stopping and the additional propulsion the belt provided. With the prototype he used about 5 minutes up the hill, without including the time spent to get free when the belt got stuck. For comparison, he used 10 to 15 minutes up the hill with the Spike Snow because he had to adjust the course a lot, which was tiring. He was so excited at the top of the hill he further said: *"If this master's thesis doesn't receive an A or B, I will speak up. This is useful and can help so incredibly many people!"*

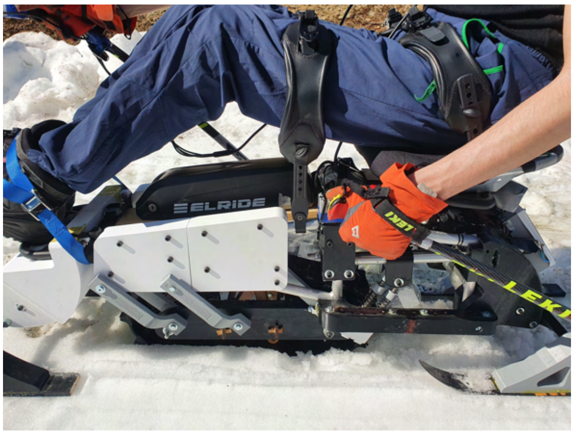


Figure 84: User lowering belt on the prototype.

(a) Picture of pit with ruler.

(b) Prototype past the pit.

Figure 85: Pictures of the measurement of the pit and the prototype past the pit up the hill.

Link to video showing the prototype with belt rolling and slider at 130 mm setting:

https://drive.google.com/drive/folders/1r-AWpaoRRzxM_sIfuVDavUZ_LWg4yItN

Figure 86: QR-code for link to video of the prototype with belt rolling and slider at 130 mm setting.

SECTION: TURNING.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.
Steering module angle: 45°
Slider distance: (1) 130 mm, (2) 100 mm
Spring load (neutral position): (1) 28.7 kg, (2) 18.5 kg

At the top of the hill, the participant tested the turning of the prototype by playing around and trying to do as tight turns as possible. The height adjustment slider was first at 130 mm, giving a spring load of 28.7 kg. The participant managed to do some turns, but found it difficult to turn hard. The slider was then moved up to 100 mm, resulting in a spring load of 18.5 kg. This lower ground pressure on the belt resulted in better turning. However, the turning radius was as large as 13-15 metres. The participant was a little afraid to do turns at the start because he did not feel comfortable leaning far out to the side. This was improved with practice, and the participant felt more comfortable when he could feel that the prototype was stable when he leaned to the sides. Afterwards, he commented that the prototype was stable and good to use. He further commented the following about the experience: *"It's a little strange having to lean the whole body so far out to the side."* The prototype was too heavy to turn 180° in the same way as the Spike Snow. It was, however, possible to lift the belt up and do many point turns, going back and forth many times to gradually turn the prototype 180° around. To save time, the prototype was instead turned by lifting the front skis off the ground and turning it around with help from one of the other test participants standing by. Figure 87 and Figure 88 shows the prototype in left and right hand turns with trails of the skis and belt left behind showing the turning path.


(a) Left turn and trails.
(b) Left turn closer.

Figure 87: Pictures of prototype turning left with trails left behind.


(a) Left to right turn with trail.
(b) Right turn with trail.

Figure 88: Left to right turn in beginning of downhill with trails left behind.

Section: Small downhill, 4°.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 17°C
Weather: Sunny, no clouds.
Steering module angle: 45°
Slider distance: 130 mm
Spring load (neutral position): 28.7 kg

"This is super fun!"

Comment from participant 1 when testing the prototype downhill.

Finally, the participant tested the prototype downhill. A strap was attached to the prototype for extra safety, in case there should be a need for extra braking. The slider was set to 130 mm, providing a spring load of 28.7 kg. Figure 89 shows the prototype tested downhill. Figure 89a shows the participant doing a right turn at the start of the hill, and Figure 89b shows the participant turning left to go straight down the hill. The participant could easily control the speed by operating the throttle. When he let go of the throttle, the prototype stopped because the belt worked as a brake. The participant said the prototype felt stable and safe downhill and further commented on the comfort: *"This is a lot more comfortable than the Spike because one can regulate the speed and actually stop in the hill."* The participant pointed out that he normally feels afraid of falling with other cross-country sit-skis when going downhill as he does not feel he has control of the speed. He further added: *"It is very nice that it stops downhill and stays still. More control makes it more comfortable. It is easy to control the speed."* Furthermore, the turning felt easier in the downhill. This might be because he felt more comfortable and had practised a bit.

(a) Right turn start of downhill.

(b) Left turn and straight down hill.

Figure 89: Prototype tested downhill with turning to adjust course.

Additional comments from the participant

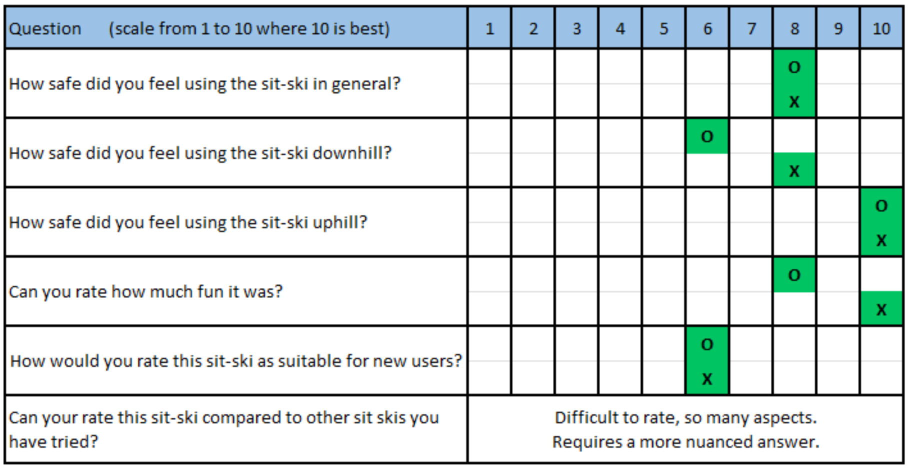
During the testing, the participant commented on the experience several times. Underneath is a collection of longer quotes made by participant 1 during and shortly after testing. All quotes, underneath and written earlier, are translated from Norwegian to English.

"I am almost out of words! I am so happy that I was able to get this opportunity and come and test this sit-ski. Several aspects that I struggle with on other sit-skis, such as stability, support, regulation of speed both downhill (breaking) and uphill (extra support through extra speed) is solved with this sit-ski! I can even join in on longer hikes with my family and go longer as I am not getting tired as fast. At the same time, I like to be able to combine the engine and extra support with double pulling so that I am actually skiing, not only driving."

"I want to contribute in lifting this idea into the world and realise it! It is so nice to feel that I can join family and friends for longer trips with a motorised sit-ski. It helps to be able to be social, keep up with the others and it would be a lot easier to get out and be more active. It would also be a lot easier to go longer and experience more and not have to turn and go back home long before my family and friends due to tiredness. The ability to have extra help from the engine when going uphill and braking when going downhill is also very good, and increases the options for tracks and routes. Regular cross-country sit-skis are often harder to get uphill and more difficult downhill when they pick up speed, so people using them often avoid large hills. This cross-country sit-ski solves that problem, you can basically go anywhere! I am convinced that this will help a lot of other people in so many ways, and it is therefore important that this idea is developed and realised!"

Comparison of the two cross-country sit-skis

After testing, the participant was asked to rate the experience of the Spike Snow and the prototype on a set of factors from 1 to 10. The rated questions are presented in Figure 90.



Question (scale from 1 to 10 where 10 is best)	1	2	3	4	5	6	7	8	9	10
How safe did you feel using the sit-ski in general?								O X		
How safe did you feel using the sit-ski downhill?						O		X		
How safe did you feel using the sit-ski uphill?										O X
Can you rate how much fun it was?								O		X
How would you rate this sit-ski as suitable for new users?						O X				
Can your rate this sit-ski compared to other sit skis you have tried?	Difficult to rate, so many aspects. Requires a more nuanced answer.									

Figure 90: Table presenting the given rating to each question. O was used to rate the Exero Spike Snow and X was used to rate the prototype.

The participant then answered some more questions about the testing and cross-country sit-skis:

- What other cross-country sit-skis have you tried?

"Handysnow 4: Very bad impression, bad seating solution and steering."

"Handysnow 5: Very good sit-ski, easy to manoeuvre and takes up little space in the car."

- How would you compare the prototype to the original Exero Spike Snow?

"This prototype and the motorised sit-ski solves a lot of the problems linked to regular sit-skis, such as the Spike Snow. The Spike is not able to supply additional propulsion uphill, and is not able to stop or allow for a break when going uphill. It is also not able to break when going downhill and can pick up speed and be uncomfortable to control downhill. As the belt acts as a break and the speed easily can be adjusted both uphill and downhill, the prototype feels safer and is a lot more comfortable as the user feels in control of the situation."

"Choosing between the sit-ski and the prototype is difficult, it depends on the intended use. Spike is lighter and it requires a lot more energy to get forward and especially up hills. The Spike Snow is therefore optimal when someone wants to exercise."

"However, the prototype is good to use for longer trips with more varied terrain as it is easy to use in both uphill and downhill. The extra support from the engine and belt also results in the user not getting tired as quickly. Therefore, the user can go for longer ski-trips! The extra help also allows the user to keep up with family and friends on trips, and facilitates a more social trip with less waiting and more fun together."

- What are the best three things about the prototype?

1. *"Definitely the hills! It can brake going downhill and can help you uphill."*

2. *"That it is possible to regulate the speed, and also better to use outside the regular ski tracks (classic ski tracks)."*

3. *"Energy saving. It saves a lot of energy to have the extra help from the belt and motor. Users can get further. Easier to get outside and go skiing without getting tired as quickly. It is also better socially as users can keep up with family and friends, and can have conversations without getting tired of double pulling."*

What are the worst three things about the prototype?

1. *"Difficult to turn 180° alone without raising the belt."*

2. *"Turning in general needs to be a bit easier. The prototype had been a lot better than the Spike had it been a little bit better at steering."*

3. *"The design of the poles, the location and design of the throttle and the cable system can be improved. Maybe by having more like a trigger throttle, like the trigger on a pistol? It was, however, good to have the cable connection one could pull out for safety."*

- Do you have any other comments?

"It would have been nice if the prototype also could be used in classic ski tracks, as long as the belt does not destroy the tracks and the functionality of the belt is not reduced, as it is so important to have the support from the belt."

6.1.2 Testing and findings with participant 2

The prototype was then tested by participant number 2. He tried both the Spike Snow and the prototype in the following sections: Flat ground, uphill, downhill and turning.

Information about test participant 2:
Weight: 75 kg
Height: 178 cm
Little to no experience with cross-country sit-skiing.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 15-16°C
Weather: Lightly clouded.
Steering module angle: 35°
Slider distance: 100 mm
Spring load (neutral position): 18.5 kg

The prototype worked well, with the belt providing great propulsion on flat ground, but it felt heavy to the participant compared to the lighter Exero Spike Snow. The participant also thought the prototype felt very stable and solid, whereas the Spike Snow felt more nimble and agile. According to the participant, it felt like the top speed of the prototype was a little slower than Spike Snow. Both cross-country sit-skis were then tested up a 40 metre long 4° hill. The participant said that the Spike Snow felt light in the beginning, but the last couple of metres felt quite exhausting. The prototype however felt a little heavy to begin with, but at the top of the hill the participant was not tired and could easily have continued up a longer hill. Testing the cross-country sit-skis downhill, the Spike Snow felt less controllable, not very stable and quite difficult to steer. The prototype however, felt very stable and by operating the throttle, the speed could easily be controlled. Turning also felt easy downhill. Even though the prototype felt very safe, it did not feel as thrilling as the Spike Snow going down. Finally, when the participant tested the turning capabilities he found that the Spike Snow required more arm strength to turn. It was, however, possible to turn both when double poling and when stationary. Turning while moving forward was easier because the side of the skis did not as easily dig into the snow. The prototype was heavier, resulting in more difficulties when trying to turn by sliding the skis sideways while not moving. When moving however, the participant turned very easily by leaning to the side and shifting the weight on the ski poles. Link to a video of participant 2 testing the turning capabilities of the prototype:

https://drive.google.com/drive/folders/1OK9oTP-QCDzdzLse3gIoVaDV6EsLEwTo

Figure 91: QR-code for link to video of participant 2 testing the turning of the prototype.

Figure 92 shows a picture of participant 2 testing the prototype and the trail left behind when turning. The smallest turning radii varied from 2 to 4 metres, while turning and not sliding with the skis.

Figure 92: Prototype tested by participant number 2.

6.1.3 Testing and findings with participant 3

Finally, the prototype was tested by participant number 3. She tested the prototype in the following sections: Flat ground, uphill, downhill and turning.

Information about test participant 3:
Weight: 60 kg
Height: 178 cm
Little to no experience with cross-country sit-skiing.

Information about the test:
Snow type/characteristics: Wet snow. Hard ice cover underneath loose, grainy and wet snow.
Trail characteristics: Cross country ski tracks without classic trail tracks.
Air temperature: 15-16°C
Weather: Lightly clouded.
Steering module angle: 35°
Slider distance: 100 mm
Spring load (neutral position): 18.5 kg

On flat ground participant 3 easily managed to double pole and operate the throttle to move forward. She also turned easily by leaning to the side. Then she tested the prototype uphill, and she moved up it seemingly effortlessly. At the top, she stopped and said it was fun and that she enjoyed the experience. Furthermore, she said that it felt comfortable and safe to use. Link to a video of participant 3 testing the prototype on flat ground and uphill:

https://drive.google.com/drive/folders/1d9pr2AMGoQVIdIFiMBSCAdcNC7hxHeGQ

Afterwards, she started turning the prototype around 180° to go downhill. With the belt in lowered position, turning around required a lot of strength, but she managed. By pushing the prototype forward a little with the ski poles, and then pushing backwards with the ski poles, distributing most power through one ski pole while also pushing sideways, she turned. She said while turning that it would probably be easier to turn if the belt was raised. Link to a video of participant 3 turning the prototype around:

https://drive.google.com/drive/folders/122myL527A-9yS7KPRQr6Fcfw9zRu5uY3

When she had turned the prototype around, she set off downhill. She easily controlled the direction and speed of the prototype by leaning to the side for steering and operating the throttle. When she was done with the testing, she commented that it was a lot of fun to use the prototype and that she saw a huge potential. She even wondered whether a further developed product based on the prototype would be available for non-disabled people too. On a final note, she commented that the steering seemed to work better for participant 2 and 3 compared to participant 1, because they felt more comfortable leaning further out to the side and sat more straight. By sitting more straight up, the centre of gravity is higher and the more weight is moved to the side when leaning out.

(a) QR-code to video testing flat and uphill.

(b) QR-code to video of 180° turning.

Figure 93: QR-codes to videos of participant 3 testing the prototype on flat ground, uphill and turning.

6.2 Videos from testing

Link to folder with videos from testing:

https://drive.google.com/drive/folders/19dGARhP-5eloRdSC2IHDH05_1NujL8Qc

Figure 94: QR-code for link to folder with videos from testing and CAD files.

6.3 Quantitative results

After both cross-country sit-skis were tested without measuring time or speed, timing equipment was used to measure the time used to cover specific distances. Three different sections were timed, flat ground section, small uphill section and small downhill section. Both the Exero Spike Snow and the developed prototype were tested and timed to compare the results. The timing equipment used was the Microgate Witty system with 1 Witty timer, 5 wireless photocells and 5 reflectors [30]. All the timed runs were completed by a male test participant with the following details: 75 kg, 178 cm tall and with no disabilities. He had skied a lot before, but was not used to cross-country sit-skiing and had never tried the Exero Spike Snow.

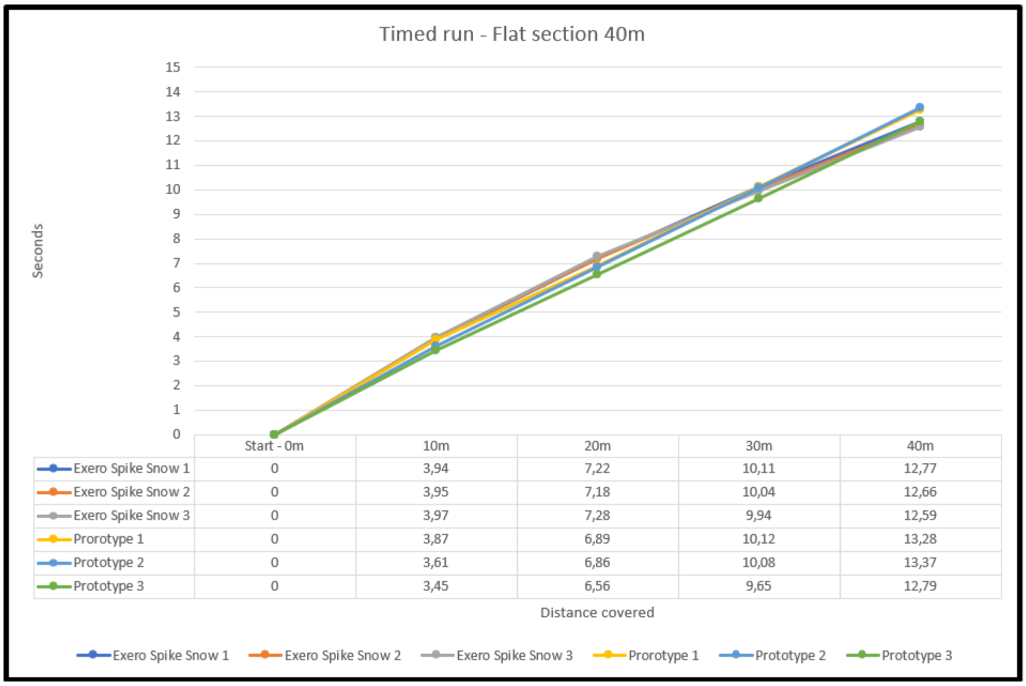
6.3.1 Flat section

A 40 metre section on a flat part of the ski track was measured up and timing equipment was placed every 10 metres to register the time at each 10 metre interval. Figure 95 shows a picture of the test section with timing equipment positioned on the sides, creating gates. First, the Exero Spike Snow was tested and three timed runs were completed. Then, the developed prototype was tested on the same stretch, also three timed runs. The test participant powered on, double poling at a high pace, but not absolute maximum power, to be able to maintain roughly the same power performance on all runs. The prototype was used with maximum throttle power, with steering mechanism at 35 degree angle and the slider at 100 mm position, providing a spring load of 18.5 kg at flat ground. The conditions were similar to the non-timed testing, with wet and slushy snow on a hard icy sole. Lightly cloudy with a temperature of 15-16°C.

Figure 95: Picture of the flat section with timing equipment on the side creating gates.

The test participant said he was tired in the arms after each run with the Exero Spike Snow, but with a two minute rest between each run he felt ready for the next run. He said that the Exero Spike Snow felt faster and lighter to ski compared to the prototype, but he was however more tired after each run with the Spike Snow than with the prototype. The prototype felt heavier, but also easier to manoeuvre and provided even propulsion the whole stretch, whereas the Spike Snow felt difficult to steer but glided more smoothly on the snow.

In Figure 96 the time results are presented with a graph and a table visualising the times at each passing point. Looking at the data collected, both cross-country sit-skis performed very equally, with the greatest time difference being 0.78 seconds. The fastest lap was the third run with the Spike Snow at 12.59 seconds and the slowest was with the prototype at 13.37 seconds. The fastest time with the prototype was 12.79 seconds, and the difference between the average time of the Spike Snow and the prototype was only 0.47 seconds. From the graph, it seems like the Spike Snow was faster in the beginning and then slower at the end of the distance compared to the prototype, which seemed to travel at a more steady speed. However, more runs and a longer distance would be necessary to verify this assumption. The average speed of the prototype was measured to be 11 km/h.



	Start - 0m	10m	20m	30m	40m
Exero Spike Snow 1	0	3,94	7,22	10,11	12,77
Exero Spike Snow 2	0	3,95	7,18	10,04	12,66
Exero Spike Snow 3	0	3,97	7,28	9,94	12,59
Prorotype 1	0	3,87	6,89	10,12	13,28
Prototype 2	0	3,61	6,86	10,08	13,37
Prototype 3	0	3,45	6,56	9,65	12,79

Figure 96: Graph and table presenting the measured times of all 6 test runs completed on the flat section. X-axis represents distance covered and Y-axis represents time in seconds.

6.3.2 Small uphill section

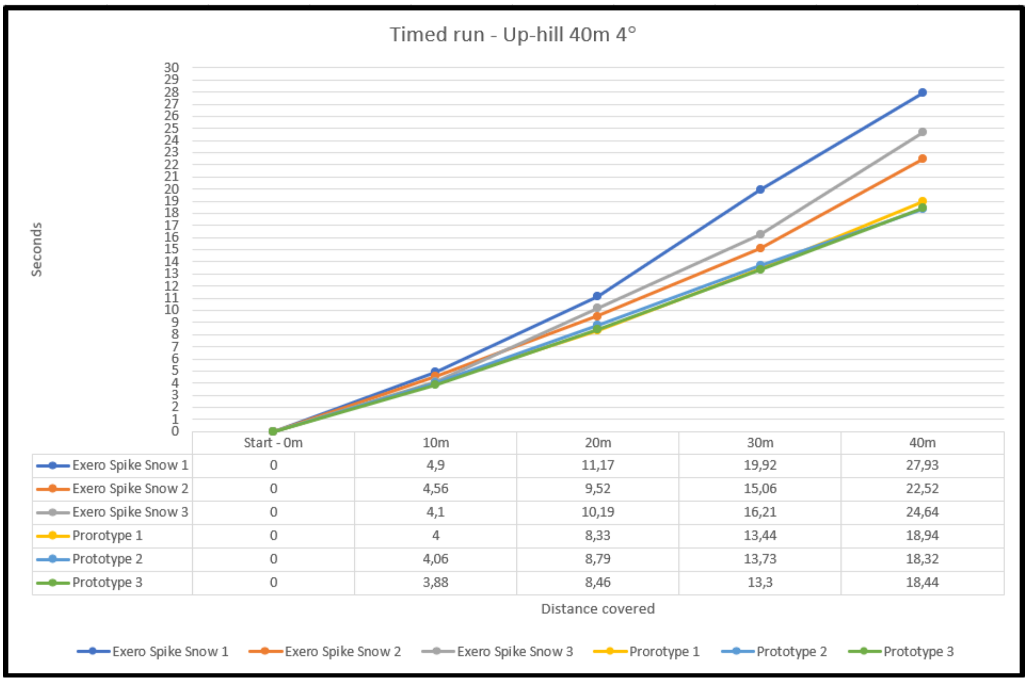
After the flat section, the timing equipment was placed in a small 4° uphill section. The gates were placed 10 metres apart, creating a 40 metre long test stretch, same as with the flat section. The same settings and procedure were implemented, with three runs on each of the cross-country sit-skis, this time with a rest of 4 minutes between each run. The participant powered up the hill, trying to get up as quickly as possible, while also having enough energy to complete all six runs. First, the Spike Snow was tested, then the prototype. A video of the third run with the prototype uphill can be viewed here:

https://drive.google.com/drive/folders/1LIz6zMLtbEM6kovNdCGduOnrEdwkOz13

Figure 97: QR-code for link to video of the third timed run uphill with the prototype.

After the testing, the participant said he was a lot more tired in the arms after double poling uphill with the Exero Spike Snow. The muscles felt really tired at the top of the hill and he said he could not have maintained the same speed had the hill been longer. It was a whole other story with the prototype. Although the construction felt heavier and not as fast and agile in the beginning, the participant was not tired at the top of the hill and could easily have continued had the hill been longer. Near the top the snow was more slushy and deeper, resulting in less traction with the belt. Nevertheless, the prototype provided propulsion assistance while also allowing for small turning adjustments without the user having to apply uneven force with the ski poles. The suspension was set to have a spring load of 18.5 kg and could have been adjusted to have a much higher spring load. This might have improved the belt traction in the parts with the deeper slushy snow.

The time results from the uphill section are presented in Figure 98. There was more variation in time between the runs with the Spike Snow compared to the prototype, as can clearly be seen in the graph. The prototype had only a variation of 0.62 seconds between fastest and slowest time, compared to 5.41 seconds for the Spike Snow. The fastest time on the prototype was 18.32 seconds and the fastest on the Spike Snow was 22.52 seconds, 4.2 seconds slower. The average time of the Spike Snow and prototype was 25.03 seconds and 18.57 seconds respectively. The difference between the average time of the Spike Snow and the prototype was 6.46 seconds. On the first attempt with the Spike Snow, the ski pole lost grip once right before the penultimate gate at 30 metres, resulting in reduced power on one of the double poling motions. This might explain why the first run was the slowest and deviated, using roughly 3 seconds longer compared to the second and third run between the third and fourth gate.



	Start - 0m	10m	20m	30m	40m
Exero Spike Snow 1	0	4,9	11,17	19,92	27,93
Exero Spike Snow 2	0	4,56	9,52	15,06	22,52
Exero Spike Snow 3	0	4,1	10,19	16,21	24,64
Prorotype 1	0	4	8,33	13,44	18,94
Prototype 2	0	4,06	8,79	13,73	18,32
Prototype 3	0	3,88	8,46	13,3	18,44

Figure 98: Graph and table presenting the measured times of all 6 test runs completed in the uphill section. X-axis represents distance covered and Y-axis represents time in seconds.

6.3.3 Small downhill section

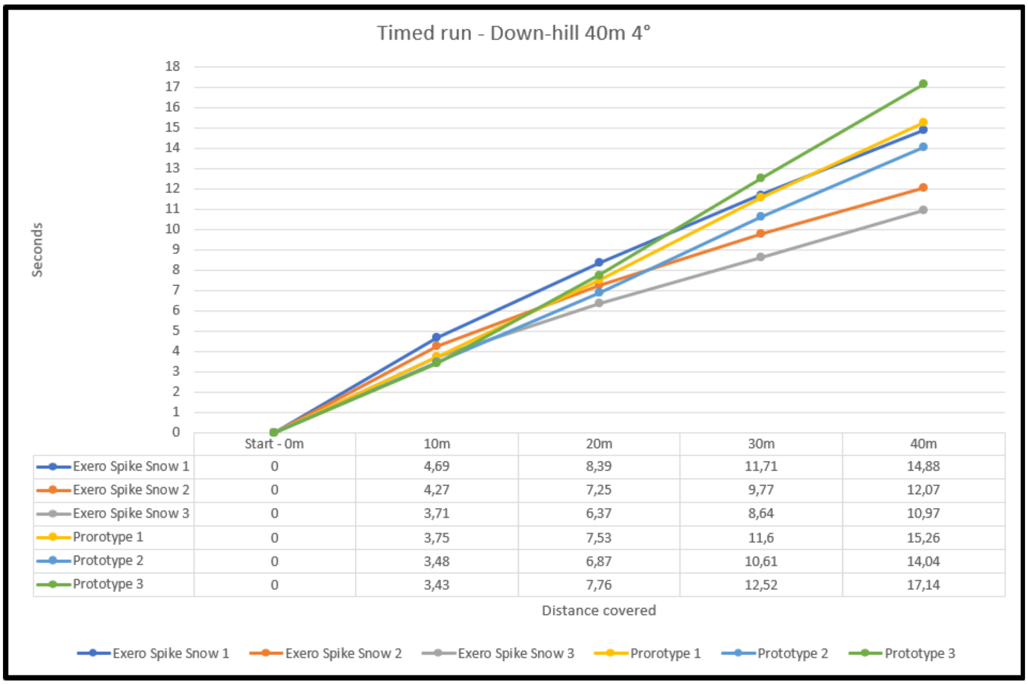
Finally, the two cross-country sit-skis were tested in a downhill section and the runs timed similarly to the flat and uphill sections. The same hill of 4° used for uphill testing was used for downhill testing. The gates were in the same position as for the uphill testing, with the top gate positioned where the hill transitioned to a flat ski track and the bottom positioned where the hill started. The same settings and procedure was used in this test also, with spring load being 18.5 kg and the snow and weather conditions unchanged.

The Exero Spike Snow was tested first. At the start of the hill, the participant double poled to gain a little speed to get down the hill. From the second gate the participant was allowed to reduce the speed by braking with the ski poles in case he felt uncomfortable with the speed. The participant placed the ski poles forward to absorb speed through the arms with "backwards double poling" action. Overall, the participant felt safe on the downhill runs, but coming to a full stop at the bottom of the hill required a couple of metres. Afterwards, the prototype was tested by first double poling and giving full throttle to reach as high a speed as possible before the second gate. Then, after passing the second gate the participant reduced the throttle and adjusted the speed to get down the hill comfortably. Had the user wanted to, he could have easily stopped in the middle of the hill by letting go of the throttle without needing to brake with the ski-poles. The participant felt very safe and comfortable downhill, being able to easily adjust course by turning slightly when necessary. A video of the third run with the prototype downhill can be viewed here:

https://drive.google.com/drive/folders/1bHaa2xxfgEVqTIlFB3Dq9AsIhKpRUF_T

Figure 99: QR-code for link to video of the third timed run downhill with the prototype.

Figure 100 presents the measured times with a graph and table of the times at each gate crossing. As visualised in the graph, the downhill section had a lot more time variation. The first run with the Exero Spike Snow might have been slower than the two other runs because the participant first had to get used to the speed and downhill to feel comfortable going faster. The difference between the fastest and slowest run was 3.91 seconds with the Spike Snow and 3.1 with the prototype. The fastest time was 10.97 seconds with the Spike Snow, and the slowest was 17.14 seconds with the prototype. The average time of the Spike Snow and prototype was 12.64 seconds and 15.48 seconds respectively. The difference between the average time of the Spike Snow and the prototype was 2.84 seconds, with the prototype being the slowest because the speed could be more easily regulated. Overall, the participant felt more safe and comfortable using the prototype downhill. This was primarily because the belt functioned as a brake and the speed could very easily be regulated, but also because it was easy to manoeuvre to stay on the right course.



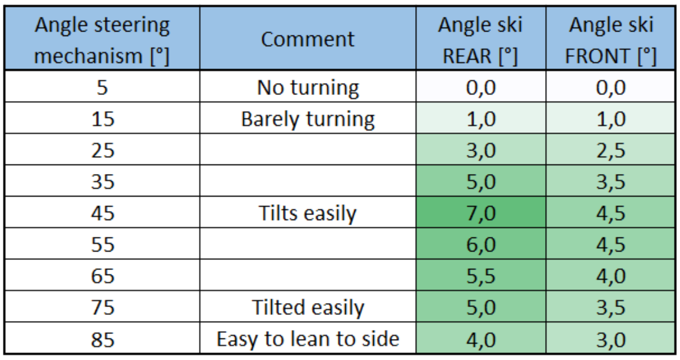
	Start - 0m	10m	20m	30m	40m
Exero Spike Snow 1	0	4,69	8,39	11,71	14,88
Exero Spike Snow 2	0	4,27	7,25	9,77	12,07
Exero Spike Snow 3	0	3,71	6,37	8,64	10,97
Prorotype 1	0	3,75	7,53	11,6	15,26
Prototype 2	0	3,48	6,87	10,61	14,04
Prototype 3	0	3,43	7,76	12,52	17,14

Figure 100: Graph and table presenting the measured times of all 6 test runs completed in the downhill section. X-axis represents distance covered and Y-axis represents time in seconds.

6.4 Testing in Laboratory

6.4.1 Measurement of steering mechanism angles

The steering mechanism was tested to measure the maximum turning angle of the skis at different angle-settings of the steering mechanisms. The sit-ski was placed on the floor with the belt in lifted position. The sit-ski was positioned such that the left side of the left skis were lined up along a straight line drawn out on the floor. In neutral turning position, the skis were pointing straight forward, perfectly aligned with the line on the floor. The test was performed as follows: The steering mechanism angle was adjusted to the angle setting to be tested. The angles ranged from 5° to 85° and were tested one at a time. The person sitting on the cross-country sit-ski during the test was 60 kg and 178 cm tall, the same person used to measure the weight distribution described in Section 5.7. The person sitting on the cross-country sit-ski prototype was strapped in with the two straps and wearing ski poles, like one would in the ski track. At each angle setting, the person leaned as far out as possible without lifting any skis above the ground, tilting the sit-ski as far to the side as possible, first to the right and then to the left side. At maximum tilt at each angle setting, a line was drawn on the floor along the left side of the left skis. This new line was drawn to intersect the long straight line, creating an angle between them. After testing of each angle setting, the angles created between the lines and the straight line were measured with a protractor. Figure 101 presents a table with the measured angles on the front and rear skis at each steering mechanism angle tested. Comments are also added to further describe the experience from the testing at each setting. The green colour scale is used to visualise the degree of turning, highlighting where the greatest angle is achieved on front and rear skis. Figure 102 shows how the steering module angle was measured on front and rear steering modules. 45° setting provided the best turning angle on the skis, with 7° on the rear skis and 4.5° on the front skis.



Angle steering mechanism [°]	Comment	Angle ski REAR [°]	Angle ski FRONT [°]
5	No turning	0,0	0,0
15	Barely turning	1,0	1,0
25		3,0	2,5
35		5,0	3,5
45	Tilts easily	7,0	4,5
55		6,0	4,5
65		5,5	4,0
75	Tilted easily	5,0	3,5
85	Easy to lean to side	4,0	3,0

Figure 101: Table presenting the maximum turning angle on the skis at different angle settings of the steering mechanisms.

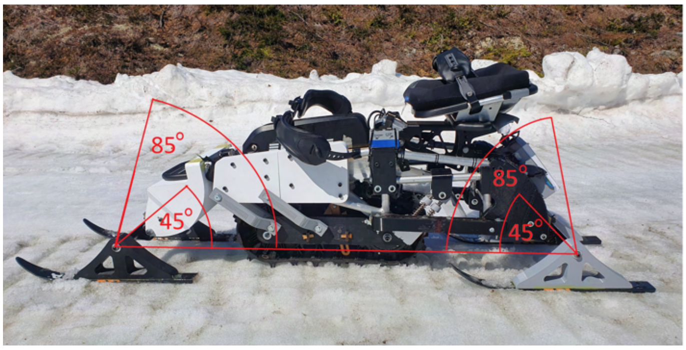
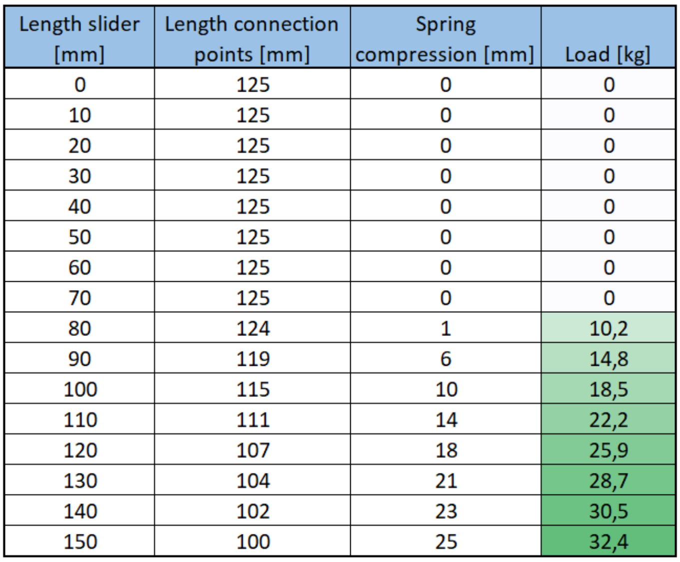


Figure 102: Angles of the steering modules explained with 45° and 85° settings visualised.

6.4.2 Measurement of height adjustment mechanism

The finalised height adjustment mechanism was tested to calculate the spring load at specific slider settings. With a person sitting on the seat of the cross-country sit-ski, the slider on the height adjustment mechanism was moved forward to lower the belt and increase the spring load on the suspension. The test was conducted in a laboratory with a flat and hard floor. Increments of 10 mm were used when adjusting and measuring. At each specific position, the length between the connection points was measured. From this length measurement the spring compression was calculated and using Hooke's law, the load was calculated at each length. The measurements and calculated compression and loads are presented in Figure 103. The green colour scale helps to visualise the change in load. The measurements shown in the table are explained in Figure 104. There was no change in the load before the belt touched the ground and the ground pressure built up to overcome the preload on the springs, happening at 70 to 80 mm. The maximum load was calculated to be 32.4 kg, which was found at maximum slider distance of 150 mm. The height adjustment mechanism was measured to use roughly 5 minutes and 40 seconds from highest to lowest position and the same time from lowest to highest position.



Length slider [mm]	Length connection points [mm]	Spring compression [mm]	Load [kg]
0	125	0	0
10	125	0	0
20	125	0	0
30	125	0	0
40	125	0	0
50	125	0	0
60	125	0	0
70	125	0	0
80	124	1	10,2
90	119	6	14,8
100	115	10	18,5
110	111	14	22,2
120	107	18	25,9
130	104	21	28,7
140	102	23	30,5
150	100	25	32,4

Figure 103: Table presenting the load through the spring system at specific distances of the height adjustment mechanism slider assuming the belt is in contact with the ground at the same height as the skis.

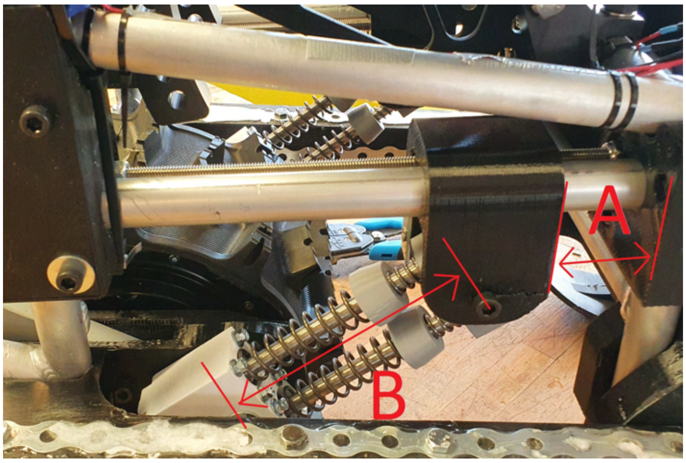


Figure 104: Distances measured and presented in Figure 103 explained. Distance A represents ”Length slider” and distance B represents ”Length connection points”.

7 Discussion

In this section, the final CCSS prototype that was tested will be evaluated and each of the objectives stated in the introduction will be discussed. In addition, the overall engineering development approach will be discussed, as well as issues and challenges that have affected the output of the project.

7.1 Overall evaluation of final CCSS prototype

Overall, the prototype was constructed primarily to test and evaluate certain functions, such as suspension and steering. Mechanisms deemed not important for the testing and performance of the functions constructed for testing were therefore fabricated as simply and time efficiently as possible. The simplest solutions were often chosen to save time and resources, as long as it was thought not to affect the performance or negatively influence the mechanisms made for testing. Glue, tape, strips, straps, Velcro and other temporary solutions were used extensively to solve issues or fasten parts for faster prototype creation and testing. Due to issues with a 3D-printer, some parts were divided and printed in smaller sections before they were then glued and reinforced with metal plates and bolts. This greatly increased the weight of the prototype and the time spent constructing the prototype. The heavier prototype most likely resulted in a less agile CCSS that did not feel as playful as the original Exero Spike Snow. By printing the parts in larger pieces on larger printers, the weight of the prototype and time spent on construction and assembly could drastically be reduced. In addition, the constructed parts were not strength optimised using Finite Element Analysis (FEA) or topology optimisation. The input loads were not known and the parts would be printed with varying infill and with varying printing quality on different 3D-printers and materials. FEA was therefore considered to be both unnecessary and undesirable because it would likely not produce any valuable or useful results. The weight of the prototype could be further reduced through weight and strength optimisation using FEA.

Transport

The prototype was transported to the testing location in a car. One strong person could lift the prototype into the car, but two people were used to avoid the risk of injuries. Without the skis, the construction could fit into the car boot. Holding the prototype in the steering trucks, two people could easily carry it to the skiing tracks from the car. The prototype was, however, not designed with transport being a high priority. As a result, the prototype lacked good lifting grips and was a lot heavier than a user would prefer. To further improve the transportability of the prototype, heavier parts, like the motor and belt, could be designed such that they could be disassembled from the prototype easily. Being able to detach the skis made the prototype easier to transport and fit in a car, but a future frame could be designed such that it can be divided in two sections under transport.

Evaluation of testing

The testing was overall very successful with the prototype being tested by three test participants in several very relevant scenarios. The mechanisms performed well both isolated and in combination. The participants were very positive and thought the prototype functioned superbly in many scenarios. Most importantly, the steering mechanism functioned in combination with the propulsion mechanism and the suspension worked as intended, providing sufficient ground pressure for the propulsion and braking mechanism. However, many scenarios were not tested due to the lack of available snow tracks. The prototype could and should be tested in more scenarios to gain more insight into the propulsion, braking and turning performance in different snow conditions, snow track conditions and trail characteristics. For instance, these include, fresh powder snow, ice, newly prepared ski tracks, old and worn ski tracks, tilted trails and steep hills. The steering mechanism should furthermore be tested in a variety of turns and the most ideal steering mechanism angle should be found through a more thorough testing on a larger area. This was not possible to find due to the snow conditions available when the prototype was tested.

Chassis, sitting position and comfort

The chassis used on the prototype was not designed in this master's project, but was the Exero Spike Snow. It was designed for two skis and to support the loads of the user down into these two skis. The prototype was, however, designed with four skis to support the loads of the user. A future chassis could be designed and strength optimised to have two front skis and two rear skis. This could avoid the need of removing the middle members of the frame to fit the motor and belt module, and as a result remove the need to construct frame stiffeners on the sides for support. The side stiffeners were manufactured on 3D-printers with high infill and then glued and reinforced, and were therefore heavy and time consuming to construct.

Steering

The steering mechanism proved to function as intended, though not as good as hoped for participant number one. This is likely because participant number one did not feel as confident leaning far out as the two other participants. They sat with a straighter back and were more comfortable leaning further out to the sides when turning, compared to the first participant. The first participant also leaned more forward, potentially altering the centre of gravity compared to the two other test participants, resulting in different steering performance. To adjust the steering mechanism to be better for all users, the springs can be adjusted to be harder and softer. Additionally, the dampers inside the springs can be changed to soften or harden the steering further. This would most likely result in a better steering experience for participant 1. The steering mechanism should be further tested to verify that a 45° angle is the best to accommodate the smallest possible turning radius. Other available steering trucks should also be investigated for their possible superior performance.

Propulsion and braking

The prototype provided great propulsion and braking assistance for all participants during testing. On flat ground and uphill, the propulsion was very sufficient. All the participants could double pole up the hill easily without becoming tired near the top. With the braking mechanism, the participants could even stop and pause in the middle of the hill, without having to lean on the ski poles to avoid sliding back down. In the downhill, the participants could control the speed by operating the throttle and stop if they wanted to because the belt would act as a brake. In future testing, it would be very interesting to investigate how steep hills the prototype could get up and down before the propulsion and braking assistance is lost or reduced.

Suspension

The propulsion and braking performance was highly dependent on a well designed and functioning suspension to maintain sufficient pressure between ground and belt for good traction. The design was quite original, with double pistons and two types of springs, as well as a long spring travel in relation to the distance between the mounting holes. The small distance was necessary to fit the suspension inside the space available and for the height adjustment mechanism to function properly. The long spring travel enabled better traction on varying snow and uneven ground. Future versions of the suspension can be designed with FEA to optimise the strength and potentially avoid having to reinforce with bolts.

Height adjustment mechanism

During the testing, the height adjustment mechanism functioned as intended. It was constructed with two high torque low speed DC motors. This was to ensure the mechanism worked even if the resistance or load would be higher than anticipated. This meant that the system was very slow. For the test, this was not a big issue, but for future versions, the user experience will most likely benefit from a faster mechanism. Furthermore, the sliders tended to move at slightly different speeds. This resulted in uneven movement when moving the sliders, most likely because one motor had a little more load than the other. The sliders were offset by a maximum of 7 mm, but usually less than 4 mm. The offset did neither seem to affect the performance of the height adjustment mechanism nor the suspension system. The uneven movement of the height adjustment sliders can, most likely, be avoided by integrating a member to connect the two sliders. One thing that was not tested on the height adjustment mechanism was the manual override. In the case of a malfunctioning height adjustment system, the system was designed to be operated manually using ratchet spanners on the bolts at the front of the system. In the case of a malfunction, the DC motors should be disengaged by moving them back slightly. Future testing should investigate whether the manual override is possible to operate by users or whether the system should be changed to better accommodate this safety feature.

Electronics

The electronics survived the testing, even though the snow was very wet. This was mainly thanks to all the tape used to protect the electronics and the installed snow spray shield. However, better and more permanent solutions, requiring less tape, should be designed for in future versions. The electronics box at the rear kept the electronics dry during testing, but it would not necessarily be capable of this in a rain shower. The battery solution was chosen for its simplicity and was great for creating a working prototype of the electronics system. At the end of the testing, when the temperature dropped, the power bank was too cold to supply electricity. It was heated up with body heat and was then possible to use again. Future versions should incorporate one battery, able to supply electricity at low temperature, to power both the motors and the circuit board. The battery should be placed inside a waterproof box along with the rest of the electronics. An ON and OFF switch should also be designed for the system so that it can easily be turned on and off.

Skis

The skis functioned well on the snow, providing low friction and enabled turning. Because the skis could not be 3D printed in one piece, the skis did not have a rear upward bend. This resulted in the skis sometimes digging down into the snow when the prototype moved backwards. Future versions of the skis could be constructed using additive manufacturing to enable easier backward movement of the prototype. The 3D-printed bindings that were glued to the skis functioned as intended, but can be strength and weight optimised to reduce weight.

Motor control and safety

The motor control proved to work well for all participants. Even participant number one with CP managed to operate the throttle to fine tune the speed he desired. However, the throttle design could be improved to further reduce the weight of the mechanism mounted on the ski pole and potentially with a different design to make the operation easier for all users. The mechanism could also be wireless to avoid having a wire between the ski pole and the prototype. Another type of safety mechanism should then be developed so that the system can be turned off by the user and others, should it be necessary. For the belt to function as a brake, it was dependent on maintaining good traction on the ground. Should the belt be lifted or otherwise not have enough traction to brake sufficiently, there should be another braking mechanism available. This could potentially be a leaver brake similar to the one found on the Tessier Eskaip [29].

7.2 Evaluation of the objectives

The main objective of this project was to develop a cross-country sit-ski prototype with steering capabilities and suspended motor driven belt track for propulsion and braking assistance. The CCSS should meet necessary user needs, be designed to accommodate a diversity of users and incorporate a proper sitting position enabling double poling. Overall, the main objective can be said to have been met, with a CCSS prototype with steering, propulsion and braking capabilities having been developed and tested to function well during use by three participants. By using an existing frame, Spike Snow, a proper sitting position was incorporated to accommodate a diversity of users. Although the foot rest was not as adjustable as the original Spike Snow, the sitting position could be adjusted to individual user preferences. Necessary user needs were discovered in the specialisation project and during the masters project. Many user needs were also discovered during the final testing, such as a possibility of softer steering, extra strap for the feet and the importance of being able to lift the belt above the ground during 180° turning. The overall objective achievement can therefore be argued to be good.

Each of the sub-objectives will be discussed more in detail underneath. As a reminder, the objectives stated in the introduction were:

- Gather knowledge to understand the sport of cross-country sit-skiing.
- Develop designs to enable steering.
- Develop designs to enable controlled propulsion and braking with a motor-driven belt track.
- Construct a test rig to develop, test and find the best solutions for steering, suspension and height adjustment mechanisms.
- Design and construct a CCSS frame and integrate the most suitable suspension and height adjustment mechanism.
- Design and construct parts to be integrated on the existing Exero Spike Snow frame to enable steering, belt track drive with suspension and regulation of belt track height.
- Test the constructed prototype and document findings.

”Gather knowledge to understand the sport of cross-country sit-skiing.”

Knowledge to understand the sport of cross-country sit-skiing was primarily gathered during the specialisation project through interviews, meetings and development and testing of prototypes. This enabled the best possible development of CCSS prototypes to meet the requirements and necessary user needs. Knowledge was also gathered during the master's project before testing, but in a smaller quantity than during the specialisation project because much knowledge was already gathered. During the testing phase in the master's project, however, new knowledge was gained about both the sport of cross-country sit-skiing, user needs and possible improvements to the developed prototype. This objective is considered reached, although new knowledge can always be gained.

”Develop designs to enable steering.”

The designs to enable steering were developed for the wooden prototype during the specialisation project. This mechanism worked during testing and was further developed for the test rig and the final prototype in the master's project. The final version incorporated a mechanism to angle the steering to find the optimum angle that gave the best steering capabilities. The steering was, however, less effective for participant number 1 than participant 2 and 3. Several possible improvements were found, including changing the dampers in the steering trucks to softer versions. With the successful steering capabilities tested, this objective can be argued to be achieved. However, the steering can, and should, be improved further to enable better steering for all users.

”Develop designs to enable controlled propulsion and braking with a motor driven belt track.”

This objective was mainly covered in the specialisation project part, but was improved in the master’s project with a better performing CCSS prototype. The motor housing developed for the wooden prototype in the specialisation project broke because it did not handle the loads. During high torque output of the belt motor, the axle slipped because the motor housing was constructed in MDF plates that did not support the loads. On the improved motor housing used in the master’s project, no parts broke because it was designed better. The propulsion system worked well for all participants and the belt also provided controlled braking. With this, the objective is considered achieved to a high degree.

”Construct a test rig to develop, test and find the best solutions for steering, suspension and height adjustment mechanisms.”

At the start of the master’s project, the plan was to develop a test rig to find the best solutions for steering, suspension and height adjustment. However, during the early stages of the construction, plans were changed to focus instead on the integration of steering and propulsion for the Spike Snow. The test rig frame was assembled, but no parts, such as steering or motor, were integrated. This objective has therefore only been reached to a low degree because the test rig was not used to develop, test or find solutions for steering, suspension or height adjustment. The mechanism to adjust the steering mechanism angle was however used on the final prototype and tested at the end of the master’s project.

”Design and construct a CCSS frame and integrate the most suitable suspension and height adjustment mechanism.”

This objective was not completed because of changes to the plan. This objective was therefore not achieved as planned in the beginning of the master’s project. Instead a new objective was created. The new objective is described next.

”Design and construct parts to be integrated on the existing Exero Spike Snow frame to enable steering, belt track drive with suspension and regulation of belt track height.”

This objective was created when the overall plan was changed from focusing on the test rig to integrating steering and motor on the Exero Spike Snow. Parts were designed and gradually fitted on the Spike Snow frame. First, steering modules were manufactured and tested to verify that the steering concept would function as intended. Then, the suspension and height adjustment mechanisms for the motor and belt module were developed concurrently to be attached on the frame. The systems were planned to be tested as soon as they were mounted on the frame, but due to delays with production, as a result of 3D-printer issues, the nearby and easily available snow trails melted before testing could be conducted. The only available testing facilities were then too far away to allow for rapid testing and iterative improvements. Therefore, the prototype was only tested in the workshop to verify that the systems functioned, before one comprehensive test was conducted at the end of the master’s project. This meant that all the parts had to be manufactured to function and not break or fail during testing because it would result in wasted time on test preparations and transport, in addition to the time spent on fixing the failure. Great efforts were made to prevent parts from breaking during testing by for instance 3D-printing with higher infill than originally planned, reinforcing with glue, metal plates and bolts and waterproofing electronics properly with tape. Eventually, this objective can be argued to be achieved to a high level.

"Test the constructed prototype and document findings."

At the end of the construction phase, the prototype was tested and the findings documented in this master's thesis. Although more testing can be conducted to potentially do more findings and find the performance limit for the systems. This objective is considered to have been reached to a high degree, although further testing is recommended as it might uncover more user needs or knowledge about the performance and function of the systems in specific scenarios.

7.3 Evaluation of the engineering development approach

Overall, the project development approach was successfully measured by the output of the project and achievement of the objectives. A successful prototype was developed and tested, producing valuable knowledge for future design development. In retrospect, it often seems easy to judge the previous decisions, but it is important to remember that many decisions in the project were taken without all the knowledge that was gained during, for instance, the final testing. By using a set-based approach [32] [16] in combination with the hunter-gather way-fairing approach [25], the prototypes were continuously adjusted according to the user needs and the new knowledge gained throughout the project. This increased the chances of developing a well functioning prototype that met the product requirements. Because the final requirements in this project were discovered through prototype testing, the approach used was advantageous. If a more traditional engineering approach had been followed throughout the project, implementing e.g. stage-gate or waterfall model [7], a final prototype could perhaps have been developed in a shorter amount of time. However, this would most likely not have yielded the same successful results because agile iterations would not have been implemented or valued to the same degree. As a result, knowledge would be gained slower or not at all during the development, before the final prototype was constructed. Only then would the prototype be tested, knowledge gained and the prototype changed based on the findings.

7.4 Effects and consequences of printer issues

Many of the designed parts were designed to be manufactured using a larger 3D-printer, but had to be divided into smaller parts and printed on smaller printers in PLA instead of ABS. This was because the larger 3D-printer stopped working properly in the early parts of the master's project. During one to two months, the printer was fixed temporarily and a few parts were printed before it stopped working again. It was not fixed and other manufacturing methods had to be found. Some parts, like the skis, were redesigned to be 3D-printed and glued on cut skis. Other parts were divided into smaller sections and 3D-printed on smaller printers in PLA with a higher infill, because of the more brittle characteristics compared to ABS in low temperatures [4] [2] [1]. These parts were then glued and reinforced with steel and bolts. This resulted in a considerable weight increase to the prototype, in addition to the time spent reinforcing and manufacturing the divided parts. The progress was delayed roughly two months because of the printer issues and because of this, the nearby testing facilities had melted before any testing could be conducted. The remaining and available snow trails were located several hours away by car. This meant that all the systems had to be constructed properly and reinforced to avoid any fractures and failures during testing. A fracture or systems failure could potentially cost a day's worth of test-preparations and transport, not to mention the time spent fixing the failure. Most importantly, the testing was delayed and iterative testing and improvements to the prototype were not possible because of these printer issues.

7.5 Effects and consequences of Covid-19

The master's project was conducted during the global Covid-19 pandemic which resulted in so-called lockdowns and restrictions for citizens in Norway. As a result, the master's project progress was affected mainly because of restrictions in how many people one was allowed or advised to meet. The project achievements were possibly also affected because it was difficult to arrange for sit-ski users to come and test the prototype during construction, due to the regulations on how many people one was allowed to meet during a week. The only testing with a cross-country sit-ski user occurred at the end of the master's project. In future work, user testing should be conducted earlier in the process to discover important user needs earlier, as this ,most likely, will result in a prototype that better meets the user needs.

8 Further work

The developed CCSS prototype can be improved in several ways to better accommodate the user needs and give a better user experience. In the subsections below, recommendations for further work related to future developments are presented. On a general note however, the prototype should be tested in more scenarios and efforts to reduce the weight should be made. Strength optimisation using FEA should be utilised.

8.1 Chassis and sitting position

In future versions of the prototype, the chassis can be redesigned for four skis instead of only two skis which the Spike Snow is made for. When redesigning the chassis frame, other materials than aluminium should be investigated. Materials such as steel and composites, as well as 3D-printed polymers should be explored. The possibility to construct the chassis in plastic using additive manufacturing is highly recommended to be looked into. Investigations into different structure types, such as monocoque, space frame or ladder chassis structures are recommended to optimise for weight and stiffness. FEA should be utilised to optimise the strength to weight ratio. Finally, the chassis should be designed with transport in mind. Perhaps with the possibility of disassembling the CCSS in smaller sections to make it easier to transport, especially in cars, and lighter to carry. A sitting position like the one from the first wooden prototype, constructed in autumn 2021, should be further investigated to see if this can result in a more comfortable experience. If the Spike Snow frame is used in future versions, the steering mechanism should be mounted on the main frame and not the foot rest. This will enable more adjustments to accommodate user preferences.

8.2 Steering module

Further testing should be conducted to find the optimum mounting angle of the steering module. If 45° is found to be the best angle for the steering mechanism, then the trucks may be mounted with a permanent angle of 45°. In addition, different steering trucks should be tested to compare their performance. Different springs and dampers in the trucks should be explored to evaluate whether it can increase the steering performance. Other possible steering configurations can be investigated if the steering does not function as intended for specific users.

8.3 Skis

The skis can be optimised for weight, stiffness and low friction on the snow. Different materials should be investigated. Future versions of the skis should be be optimised for the most suitable length. It might be the case that longer skis will result in less frictional drag and improve the steering performance. Additive manufacturing should be utilised in the construction of skis to incorporate rear tips to accommodate reverse CCSS movement.

Furthermore, width adjustment of skis to fit in and outside classic cross-country ski tracks should be implemented. This will enable a more convenient use because the CCSS skis will follow the tracks. However, it is important to mount the skis wide enough to maintain a stable ride on the CCSS, especially when turning. The possibility of integrating side skis to increase the stability can be looked into. This would possibly increase the stability, but also perhaps increase the frictional drag and weight of the CCSS.

8.4 Height adjustment module

The height adjustment mechanism should be further developed to be more ergonomic and user friendly. The mechanism can be made faster by using faster motors and the electronics should be designed to better tolerate cold temperatures. In the highest position, the belt can be lifted higher to reduce drag in deep snow or uneven terrain. To avoid the sliders on the sides from becoming uneven, a member can be integrated to connect the sliders. The electronics can further be designed to be more compact and with one battery integrated in a water protected box. To turn the system on and off, a switch should be integrated.

8.5 Suspension module

Further testing should be conducted to optimise the spring coefficient by changing the springs. Dampers can be added to avoid uncontrolled oscillations. If a new frame is designed, the suspension can be improved by increasing the maximum spring travel if it is found to be advantageous. Investigations into new designs of the suspension module is encouraged.

8.6 Motor and belt module

The motor housing should be constructed in a material that withstands water. The parts in MDF-plates should be manufactured in metal or plastic instead. A belt that fits the belt wheels should be chosen to avoid jerky and loud operation. In the prototype, lubrication between the belt and belt wheels was used to reduce the jerky motion. Future versions should investigate whether the electric motor cogwheel should be manufactured in a different material to reduce wear on the parts. The gap between the cogwheel parts around the motor should be minimised and the connection between the parts should be designed so that the belt teeth are not hit by bolts and screws. A shorter motor axle could potentially be used to fit better inside the Exero Spike Snow. Furthermore, the motor and belt module can be designed to be detachable, reduce weight during transport and enable a lighter CCSS for use without motor.

8.7 Motor control and safety

The motor control can be optimised in a variety of ways. Firstly, the motor control of the CCSS should be modified so that it cannot be used like a snowmobile. The user should be required to double pole for the motor to provide propulsion. This can possibly be done by integrating a uniaxial strain gauge load cell. Research into the use of this in ski poles seems promising [15]. In addition, the motor control unit screen should be placed so that it is easier to see during double poling and use of the CCSS. The possibility of a heads-up-display in glasses or goggles may be worth exploring.

The motor speed regulation should be further investigated. The integration of a foot pedal or a thumb throttle mounted differently on the ski pole could be beneficial depending on the user. It is very important that the motor control is user-friendly and safe to use. Furthermore, an automagical speed regulation control should be explored. By regulating the speed depending on the heart-rate of the user, the force through the ski poles or the angle of the ground or slope, this may be achieved.

In case the belt is not in contact with the ground or not providing sufficient braking effect, another braking mechanism should be integrated to provide additional safety and user comfort.

Finally, a safety mechanism should be integrated to turn the power OFF in case of an emergency or if the user falls off the CCSS.

9 Conclusion

Conventional cross-country sit-skis available on the market today are valuable equipment to Paralympic cross-country skiers and highly tailored to the user. However, the equipment is difficult to steer, can be demanding and scary downhill and prove exhausting uphill. Through this project, knowledge was gathered and user needs mapped before prototypes were developed. In the concept and prototyping phase, design possibilities were explored and knowledge about the construction and needs of a cross-country sit-ski was gained. Based on the knowledge and prototypes, a final prototype was constructed. Through testing with three test participants in cross-country ski trails the final prototype was analysed and evaluated for performance and general design.

The final prototype proved highly functional and stable in the tests, however, the design would benefit from further improvements. The developed final prototype worked well on flat ground, for turning and up and down a small hill of 4°. The skis were placed too wide to fit properly in the classic ski tracks, but functioned well in the skating track. The steering worked well for two of the participants, but could be improved to function better for the first participant, by for instance changing to softer dampers in the trucks. Other issues discovered through testing include the added weight of the prototype, mostly as a result of printer issues, skis that were not made for reverse motion and the limited adjustment of the foot rest because of the way the front steering module was mounted. Recommendations for further work include and are not limited to; an improved chassis structure, further testing of the steering module and belt traction in more scenarios, faster belt height adjustment and better motor control.

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Appendix

A Circuit diagram of electronics in the height adjustment mechanism

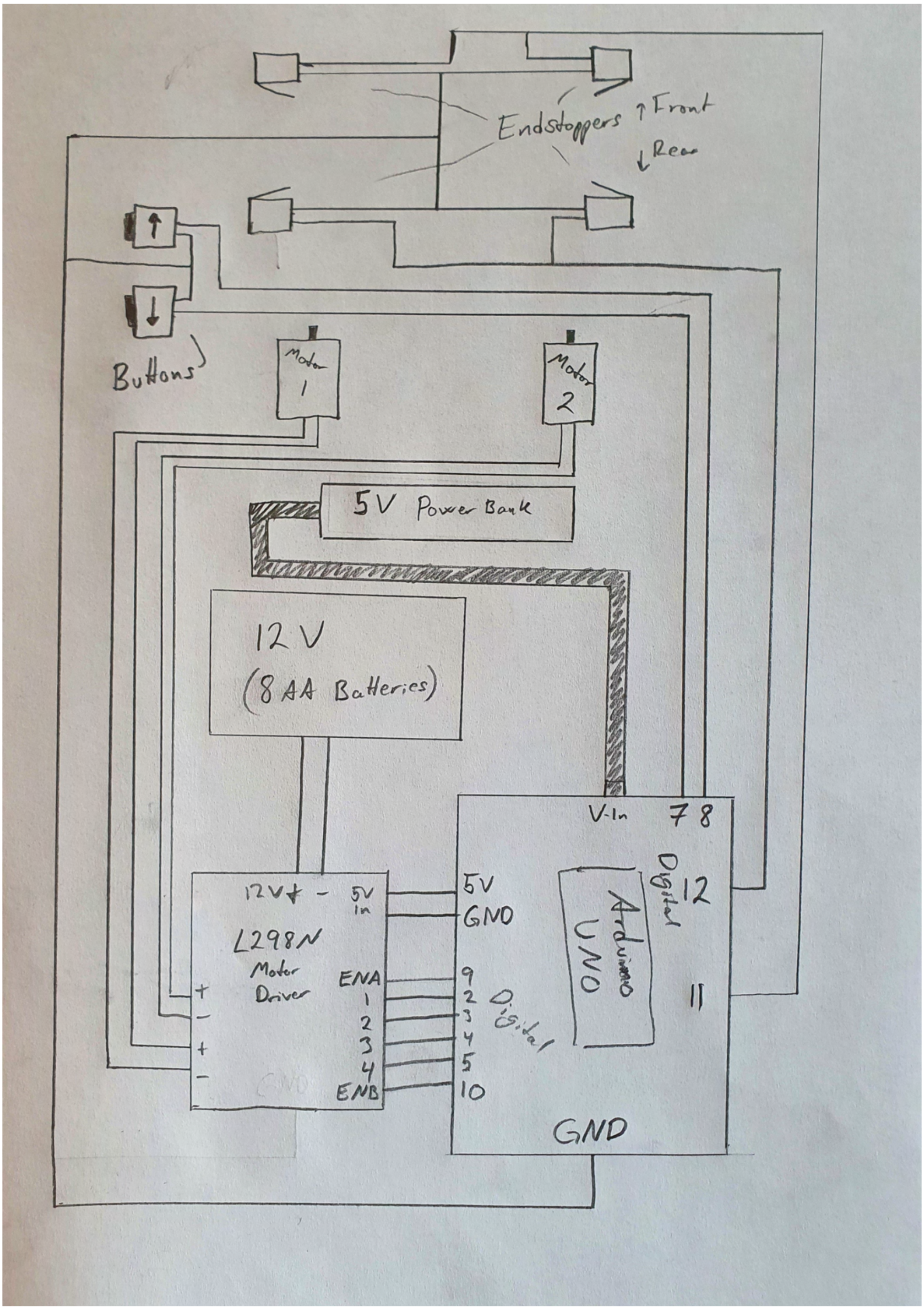

Figure 105: Circuit diagram of the electronics in the height adjustment mechanism.

B Arduino code for the height adjustment mechanism

The Arduino code used for the electronics of the height adjustment mechanism is presented in the following pages.

```
// This is the code used to drive the height ajustmet mechanism
on the cross-country sit-ski prototype developed at TrollLABS,
NTNU, Spring 2022.
// Written by Henrik Krohg Stabell Spring 2022 as part of
Master's thesis project.

int motor1pin1 = 2;
int motor1pin2 = 3;

int motor2pin1 = 4;
int motor2pin2 = 5;

int leftButton = 8;
int rightButton = 7; // buttons

int frontEndstop1 = 11;
int rearEndstop1 = 12;  // Endstoppers


void setup() {
  // put your setup code here, to run once:
  pinMode(motor1pin1, OUTPUT);
  pinMode(motor1pin2, OUTPUT);
  pinMode(motor2pin1, OUTPUT);
  pinMode(motor2pin2, OUTPUT);


  pinMode(leftButton, INPUT_PULLUP);
  pinMode(rightButton, INPUT_PULLUP); // inputs w internal pullup
resistors

  pinMode(frontEndstop1, INPUT_PULLUP);
  pinMode(rearEndstop1, INPUT_PULLUP);


  pinMode(9, OUTPUT);
  pinMode(10, OUTPUT);
}

void loop() {
```

```
  // put your main code here, to run repeatedly:

  int leftPinState = digitalRead(leftButton);
  int rightPinState = digitalRead(rightButton); // set value
names for read data

  int frontEndstopState = digitalRead(frontEndstop1);
  int rearEndstopState = digitalRead(rearEndstop1);

  if (frontEndstopState == HIGH and rearEndstopState ==HIGH) {
//if front and rear endstop is NOT pressed ....

        if (leftPinState == LOW) { // if left button is pressed
...

          //Controlling speed (0 = off and 255 = max speed):
          analogWrite(9, 250); //ENA pin
          analogWrite(10, 250); //ENB pin

          //Controlling spin direction of motors:
          digitalWrite(motor1pin1, HIGH);
          digitalWrite(motor1pin2, LOW);

          digitalWrite(motor2pin1, HIGH);
          digitalWrite(motor2pin2, LOW);

    //  delay(5000);
      }


      else if (rightPinState == LOW) { // if right button is
pressed ...


          //Controlling speed (0 = off and 255 = max speed):
          analogWrite(9, 250); //ENA pin
          analogWrite(10, 250); //ENB pin

          //Controlling spin direction of motors:
          digitalWrite(motor1pin1, LOW);
```

```
          digitalWrite(motor1pin2, HIGH);

          digitalWrite(motor2pin1, LOW);
          digitalWrite(motor2pin2, HIGH);

      }



      else { // if neither button is pressed ...

          digitalWrite(motor1pin1, LOW); // nothing happens
          digitalWrite(motor1pin2, LOW);

          digitalWrite(motor2pin1, LOW);
          digitalWrite(motor2pin2, LOW);
      }


  }


  if (frontEndstopState == LOW) {  //if front endstop is pressed
....

          analogWrite(9, 250); //ENA pin
          analogWrite(10, 250); //ENB pin

          //Controlling spin direction of motors:
          digitalWrite(motor1pin1, HIGH);
          digitalWrite(motor1pin2, LOW);

          digitalWrite(motor2pin1, HIGH);
          digitalWrite(motor2pin2, LOW);
  }



  if (rearEndstopState == LOW) {  //if rear endstop is pressed
....
```

```
          //Controlling speed (0 = off and 255 = max speed):
          analogWrite(9, 250); //ENA pin
          analogWrite(10, 250); //ENB pin

          //Controlling spin direction of motors:
          digitalWrite(motor1pin1, LOW);
          digitalWrite(motor1pin2, HIGH);

          digitalWrite(motor2pin1, LOW);
          digitalWrite(motor2pin2, HIGH);

  }



//  digitalWrite(motor1pin1, LOW);
//  digitalWrite(motor1pin2, HIGH);
//
//  digitalWrite(motor2pin1, LOW);
//  digitalWrite(motor2pin2, HIGH);
//  delay(5000);


}
```

C Specialization Report Autumn 2021

The report written for the Specialization project in autumn 2021 is presented in the following pages.

NTNU
Kunnskap for en bedre verden

DEPARTMENT OF MECHANICAL AND
INDUSTRIAL ENGINEERING

TMM4560 - ENGINEERING DESIGN AND MATERIALS

SPECIALIZATION PROJECT

Development of a cross-country sit-ski prototype with steering capabilities and motor for propulsion and braking assistance.

Author:
Henrik Krohg Stabell

Trondheim, Norway
20 December, 2021

Preface

This report was written as part of the Specialization Project in the course TMM4560 - Engineering Design and Materials at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology in autumn 2021.

The purpose of this project is to develop a cross-country sit-ski prototype with steering capabilities and motor for propulsion and braking assistance based on the previous related work conducted at the Department of Mechanical and Industrial Engineering at the Norwegian University of Science and Technology. In the project I collaborated with Dina Longva Zimmermann. Dina Longa Zimmermann focused mainly on the sitting position and chassis construction, while I focused on the integration of a motor and steering capabilities. This report presents my work, although some work such as the interviews and knowledge gathering was conducted in collaboration with Dina Longva Zimmermann.

For this project motor, battery and motor control from the previous year were used. They were sponsored by Elsykkelbutikken Trondheim in 2019.

The following material was supplied by Exero Technologies: Two steering modules, a sit-ski frame from an Exero Spike Snow and a seat.

The skis used in this project were supplied by Bjørn Åge Berntsen at SIAT.

I would like to show my gratidute to,

Knut Einar Aasland, Supervisor

Bjørn Åge Berntsen, Co-supervisor

Sindre Wold Eikevåg, Co-supervisor

Senter for Idrettsanlegg og teknologi (SIAT)

Mathias Thorkildsen Berg, Exero Technologies

Stian Kvalvik, Exero Technologies

Viljar Aasan, Beitostølen Healthsports Center

Elsykkelbutikken Trondheim

Ailin Østerås

NTNU, Trondheim 20.12.2021

Henrik Krohg Stabell

Abstract

This project aims to develop a cross-country sit-ski prototype with a propulsion assistance and resistance braking motor, as well as steering capabilities and to gain knowledge needed to design and produce a low quantity of units of an improved version. This is for the purpose of improving the quality of life, feeling of independence and training for people with spinal cord injuries and walking disabilities in cross-country skiing, because the solutions and products available on the market today are not sufficient and need improvements.

The cross-country sit-ski is important and valuable for people with walking disabilities and increase their quality of life by allowing them to go skiing and access nature. However, the products available today are suitable for flat ground, but prove demanding and exhausting in uphill and can be difficult to steer in turns and brake in downhill. To address this, several prototypes were developed to test concepts and learn about the design possibilities. A final cross-country sit-ski prototype with propulsion, braking and steering capabilities was constructed based on the developed prototypes and the knowledge gained though the development process.

A thorough testing was conducted in cross-country ski trails with three test participants. In the test the cross-country sit-ski was analysed in scenarios such as, flat ground in and outside classic ski tracks, left and right turns, as well as descending and ascending both a small slope and a long steep slope. Results showed a stable and highly functioning prototype with both propulsion, braking and steering capabilities working. However, adjustments are required for the design to be ready for a low quantity production. Recommendations for further work include and are not limited to, an improved chassis structure, a more solid steering module, a strength optimized suspension module and an improved sitting position to increase comfort for the user.

Sammendrag

Dette prosjektet tar sikte på å utvikle en langrenns- sit-ski-prototype med fremdriftsassistanse- og motstandsbremsings-motor, samt styreegenskaper og å tilegne kunnskap som trengs for å designe og produsere et lite antall enheter av en forbedret versjon. Dette med det formål å bedre livskvalitet, følelse av selvstendighet og trening for personer med ryggmargsskader og gangvansker i langrenn, fordi løsningene og produktene som finnes på markedet i dag ikke er tilstrekkelige og trenger forbedringer.

Langrenns-sit-ski-kjelken er viktig og verdifull for mennesker med gangvansker og øker livskvaliteten ved å la dem gå på ski og få tilgang til naturen. Produktene som er tilgjengelige i dag er imidlertid egnet for flatt underlag, men viser seg krevende og utmattende i oppoverbakker og kan være vanskelige å styre i svinger og bremse med i nedoverbakker. For å forsøke å løse dette ble det utviklet flere prototyper for å teste konsepter og lære om designmulighetene. En endelig langrenns-sit-ski-prototype med fremdrifts-, bremse- og styre-egenskaper ble konstruert basert på de utviklede prototypene og kunnskapen som ble tilegnet gjennom utviklingsprosessen.

Det ble gjennomført en grundig testing i langrennsløyper med tre testdeltakere. I testen ble langrenns-sit-ski-prototypen analysert i scenarier som flatt underlag i og utenfor klassiske skispor, venstre- og høyresvinger, samt ned- og oppover både i en liten bakke og en lang bratt bakke. Resultatene viste en stabil og svært fungerende prototype med både fremdrifts-, bremse- og styreegenskaper. Det kreves imidlertid justeringer for at designet skal være klart for å produsere et lite antall av langrenns-sit-skien. Anbefalinger for videre arbeid inkluderer, og er ikke begrenset til, en forbedret chassisstruktur, en mer solid styremodul, en styrkeoptimalisert fjæringsmodul og en forbedret sittestilling for å øke komforten for brukeren.

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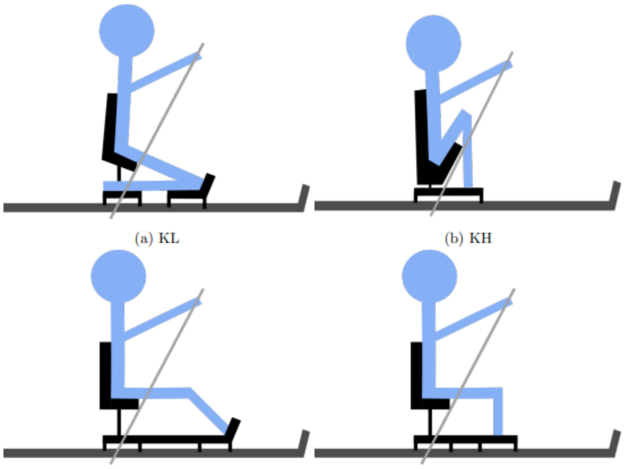
1 Introduction

1.1 Background

In recent years, para sports have gained growing attention and the equipment is increasingly being customised to the users, however the available equipment presents limitations and challenges for the users. For people with spinal cord injuries or walking disabilities who cannot go cross-country skiing by standing on their legs a cross-country sit-ski is used. A cross-country sit-ski (CCSS) consists of a pair of cross-country skis and a seat configuration connected to the skis. Depending on the sitting position, the user sits on the knees or on the but with legs forward. The cross-country sit-skis are great equipment allowing the users to access the ski trails, be active and experience nature. Users of CCSSs include, but are not limited to, people with cerebral palsy, spinal cord injuries and amputees.

There are four main sitting positions used in cross-country sit-skiing; KL, KH, KLS and KN [6] [1]. Figure 1 shows these positions. (a) shows the KL position where the knees are placed lower than the hips and the calves and feet are behind the knees. This position can be used with or without a back support. (b) shows the KH position where the knees are placed higher than the hips and normally includes a back support. (c) shows the position where the knees and legs are straight forward, called KLS position. In this position there is often an angle in the knees. (d) shows position KN, where the user is in a neutral sitting position with knees and hips bent at 90°angles. The position used in a CCSS primarily depends on individual user preferences.



(a) KL (b) KH

(c) KLS (d) KN

Figure 1: The four main sitting positions in cross-country sit-skiing.

Source: [1]

There are numerous amounts of cross-country sit-ski constructions available to users. These can be divided into two classes, tailored and non-tailored. Tailored cross-country sit-skis are bespoke and are made to fit only the one person it was made for. This is typically the case for athlete CCSSs used in competitions. Non-tailored CCSSs are not customised to fit only one person, but designed to fit a general user group. These types are often designed with seat and supports to be adjustable to fit individual user preferences. Three commonly used non-tailored CCSSs are presented below.

Skeno Power

Skeno Power is a CCSS developed by Norwegian based Skeno AS [15]. Figure 2 shows the CCSS. It is designed to be used with sitting position KL and can be modified to accommodate individual user needs, especially for amputees. The CCSS has several straps to fasten the user and a brake lever positioned at the front between the knee supports. Users can choose whether to mount the structure on cross-country skis or on a wheel based platform. The chassis is mostly aluminium, while the supports are made out of composite materials.

Figure 2: Skeno Power cross-country sit-ski.

Source: [15]

Exero Spike Snow

Exero Spike Snow is a CCSS developed by the Norwegian company Exero Technologies [21]. It is a light aluminium structure designed for position KLS, but does not have a back support. The seat can be angled to accommodate individual users preferences. Three straps are used to fasten the user. The Exero Spike Snow is shown in Figure 3.

Figure 3: Exero Spike Snow cross-country sit-ski.

Source: [21]

Tessier Eskaip

Tessier Eskaip is a light and highly customizable cross-country sit-ski made by the french company Tessier [22]. The aluminium frame is fully adjustable, enabling individual settings for seat height, seat angle, footrest and centre of gravity. The CCSS can also be used with a back support and accommodates for KH, KN and KLS positions. Optional brake levers on the side provide some speed control. Several seats are compatible and a plate located at the rear allow for push assistance by a fellow skier if needed. Two to three straps securely fasten the user. The Eskaip is shown without back support in Figure 4.

Figure 4: Tessier Eskaip cross-country sit-skiing.

Source: [16]

1.2 Problem description

Paralympic cross-country skiing equipment is tailored and centred around the user, however the cross-country sit-skis available today lack proper steering and would benefit from propulsion and braking assistance. The conventional CCSSs available available today are suitable for flat ground skiing, but prove demanding and exhausting in uphill and can be difficult to steer in turns and brake in downhill. This can result in both dangerous and scary situations for CCSS users and others nearby. In addition, the skiing experience can be reduced if the activity proves too demanding and exhausting. There is therefore a great need for a CCSS with better steering and braking possibilities to increase the safety and comfort of cross-country sit-skiing. Propulsion assistance would also benefit the user experience and improve the quality of skiing for CCSS users.

1.3 Previous work

Paralympic cross-country skiing is a field with limited research and not many academic publications are available, however important research has been conducted locally at the Norwegian University of Science and Technology. In the spring of 2018 a master's thesis was conducted where a prototype of a cross-country sit-ski on wheels with steering abilities was developed. This prototype would later be further developed into what is now the Exero Spike [20]. Through the research and development a lot of knowledge about steering possibilities and sitting positions was gained. Additive manufacturing was utilised extensively to build prototypes. For the steering module on the prototype, channel trucks similar to that on the Exero Spike were used. [3]

In the spring of 2021 a CCSS prototype with propulsion and braking capabilities was developed as part of a master's thesis. The developed cross-country sit-ski was designed for a KL sitting position with adjustable seat height and seat angle. A belt track was integrated inside the aluminium frame to provide propulsion assistance. An electrical bicycle hub motor of 250 watts was used for propulsion, supplied by a battery placed in a backpack worn by the user. The motor was controlled by using a motor control unit with a thumb throttle connected to a ski pole. Through tests the cross-country sit-ski performed well and provided great additional propulsion, especially in uphill. An additional and unanticipated finding was that the the belt track also provided controlled braking in downhill slopes. However, the CCSS did neither provide controlled steering, nor accommodate other sitting positions than KL. The master's thesis was a continuation of a master's thesis project on the same topic conducted spring 2020. Figure 5 shows the developed prototype and the main components. To the author's knowledge, no other cross-country sit-ski with propulsion and braking assistance has been developed. [1]

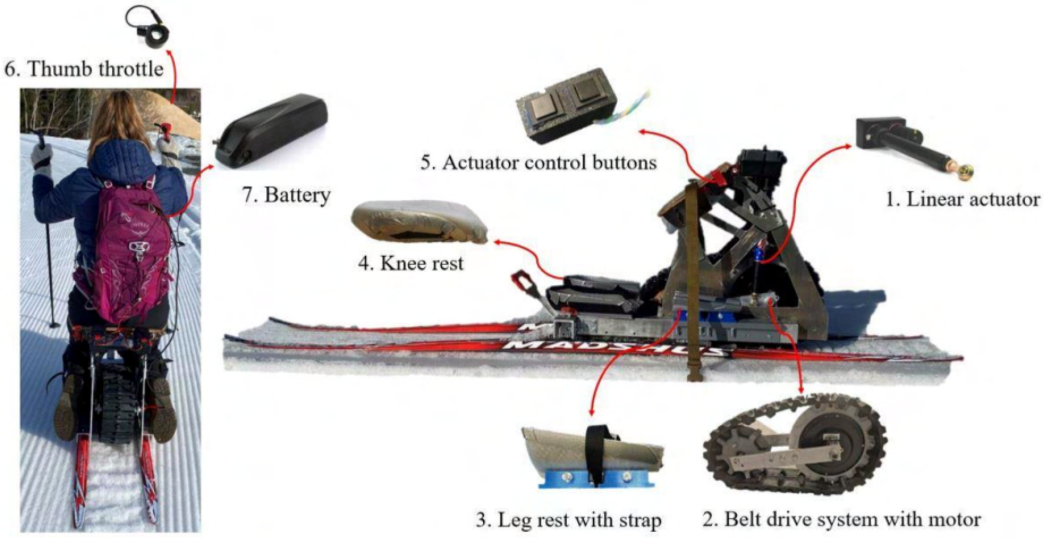


Figure 5: Prototype developed through previous research at NTNU spring 2021.

Source: [1]

1.4 Project scope

The objective of this project is to develop a cross-country sit-ski with propulsion and breaking assistance, and steering capabilities. The CCSS should meet necessary user needs, be designed to accommodate a diversity of users and incorporate a proper sitting position enabling double poling. The overall vision of this project is to make cross country skiing accessible for everyone.

Furthermore, relevant laws and regulations should be followed. The developed CCSS should therefore not have an auxiliary engine with greater nominal effect than 250 W and should have a mechanism preventing the contraption from reaching greater speeds than 25 km/h with engine power. At this greater speeds, the motor power should not provide propulsion. In addition, for start-up assistance the motor alone is allowed to provide propulsion of up to 6 km/h. [12] [13] [17]

1.5 Thesis structure

This paper is divided into seven sections: Introduction, Development approach and methodology, Prototyping process, Final prototype, Testing and discussion of final prototype, Further work and Conclusion. In the **Development approach and methodology** section the development approach and methodology applied in the project is explained. First, the needfinding process is explained, then theoretical concepts development and prototyping are described before finally prototype testing is clarified. Later, in the **Prototyping process** section the prototypes created throughout the project are presented and their value generation specified. The **Final prototype** section describes the composition of the final prototype developed based on the prototypes and knowledge gained in the previous two sections. Afterwards, in the **Testing and discussion of final prototype** section the final testing with results is presented and evaluated. Recommendations for future work is presented in **Further work** section before the **Conclusion** at the end of the paper.

2 Development approach and methodology

The development approach chosen for this project was a combination between set-based concurrent engineering [11] [23] and the hunter gather wayfaring approach used specifically in fuzzy frond end projects [18]. Overall, the process was divided into four stages completed in chronological order: Knowledge gathering and learning process, Theoretical concepts and sketching, Prototyping and model building, and finally, Prototype testing. In the Knowledge gathering and learning process stage, the focus was on gathering as much knowledge about the field of Paralympics, cross-country sit-skis and gather information from relevant previous work. Then, in the Theoretical concepts and sketching stage, theoretical concepts where developed and sketches of the most viable concepts where made. This was followed by the Prototyping and model building stage where prototypes and models where constructed and tested to enable a constant learning process during the development. Eventually, the final prototype was more thoroughly tested to learn what worked with the developed concept and find points of improvement. Even though the project primarily followed these four stages in chronological order, work was done in all four concurrently and in smaller sets and iterations as proposed [23] [18] [4] [11]. As the project developed new knowledge was found and new designs where proposed, requiring further knowledge gathering and testing which in turn resulted in new design specifications and alterations.

2.1 Knowledge gathering, interviews, learning process and needfinding

The knowledge gathering and learning process stage was the initial phase of the project, where the overall goal was to explore and gather knowledge relevant for the project. This included knowledge about the concept of Paralympic skiing, need-finding, the generation of as much insight into cross- country sit-skis, issues with available equipment and the development of a view from the prospective of the user of such equipment. Through a meeting with representatives from Exero and Beitostølen Health Sport Centre Norway, valuable insight into the Paralympic equipment was gained. In addition, previous conducted research relevant to the project was explored and interviews with CCSS users were conducted.

Moreover, exploration into previous relevant research and testing of both the CCSS prototype developed at NTNU in spring 2021, shown in Figure 6 [1] and the Exero Spike Figure 7 [20] set the fixed points in terms of design choices for this project. The previous research product development of the Exero Spike gave valuable insight into possible steering mechanisms [3]. Based on tests and evaluation of the CCSS prototype developed spring 2021 as well as the findings [1] a belt driven electric motor system was chosen as the propulsion and braking assistance. The seat and sitting position from the prototype were used as reference for a possible knee sitting CCSS, although the overall desire was to develop a CCSS where all the four sitting positions introduced earlier could be integrated and used. Based on the positive experience from the Exero Spike, a similar turning mechanism would be preferred if possible. This would allow for turning, but would also require four independent skis.

Figure 6: Prototype developed at NTNU spring 2021.

Source: [1]

Figure 7: Exero Spike.

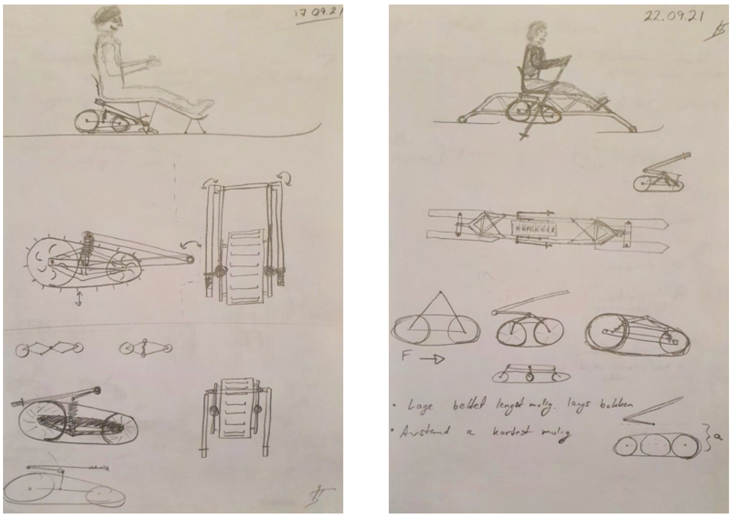
Source: [20]

Furthermore, interviews with two users of cross-country sit-skis were conducted to increase the insight into aspects of cross-country sit-skiing, as well as the problems associated with the use of such equipment. The interviewed users were both frequent users of cross-country sit-skis. One of them had a high spinal cord injury, the other had cerebral palsy (CP). Through the interviews the users stressed the importance of stability and issues with steering. Steering and braking was normally controlled using the ski poles. Uphills were described as exhausting if the hill was more than to 2 meters in elevation. This problem was usually solved by avoiding steep hills or pulling help up the slope by another skier. Additionally, the interviewed users stressed the importance of a good and comfortable sitting position and other less obvious issues such as reduced gripping force for people with CP and different requirements depending on the height of the spinal cord injury. The most comfortable sitting position was said to be the sitting position KLS, with feet forward. When presented with the idea of a motorised belt driven CCSS, they where very positive and welcomed the concept. However, two important concerns were pointed out: the possible destruction of ski trails by the belt and that the CCSS should be constructed to be convenient and easy to handle for the user.

To summarise, through this initial need-finding and knowledge gathering phase the following challenges where discovered: Arm and gripping strength, Sitting position, Steering, Braking, Convenience and user friendliness, Fit in the classic ski tracks and Balance. Through this phase in the project the following fixed design points were decided on: A belt driven electrical motor system, Steering capabilities and A suspension module to control for uneven terrain. The sitting position was not decided on, although a KLS position was desirable for comfort. These where the initial “set needs” for the prototype to be developed. However, if new knowledge gained later in the project would deem it necessary, these fixed points could be altered to construct a more suitable end prototype.

2.2 Theoretical concepts and sketching

In the early stages of the project, theoretical concepts to accommodate the user needs were developed and sketches were created to visualise the variety of possibilities. These theoretical concepts and sketches were constructed in conjunction with the need-finding stage. Figure 8 show two sketches of the many concepts that were developed. The sketch in Figure 8a shows a CCSS with one pair of skis, a belt drive system with suspension and height adjustment and a user in sitting position KLS. Figure 8b shows a CCSS with two pair of skis, a truss structure chassis, a belt drive system with suspension and height adjustment and a user in sitting position KLS. The height adjustment of both concepts were designed to be operated using a lever arm. By incorporating a height adjustment mechanism for the motor and belt, the issues with traction and height differences in the classic ski track could potentially be accommodated [1]. The two sketches show the lever arm in opposite directions and with slight variations in lengths and positions of members. From the concepts and sketches, 3 dimensional prototypes were created.



(a) Sketch 1, one pair of skis (b) Sketch 2, two pair of skis

Figure 8: Examples of early stage sketches of concepts for a cross-country sit-ski with motor.

2.3 Prototype and model building to fill knowledge gaps.

In the prototyping stage concepts were further developed and investigated in 3 dimensions, primarily physical models, to give answers to design questions. Prototyping was used to answer questions about design, to learn what worked and how it worked and to gain relevant knowledge as time and cost effectively as possible. By developing prototypes cost and risk were also reduced and most importantly, the possibility to discover and explore opportunities was increased [18]. These are some of the most important properties of prototypes [14] [7]. In the prototyping process, there was also a hope of detecting unanticipated phenomena and discover unknown unknowns [19] [8], but this would also be possible to discover in the user testing phase or through experience prototyping [5].

Throughout the project prototypes of varying form and function were developed. The prototypes ranged from focused to comprehensive [23] and from low to high fidelity and resolution [7] depending on what they were trying to answer or gain knowledge about. Initially, physical prototypes of low fidelity and low resolution were developed. These included Lego and paper models. Both looks-like [23] prototypes, such as the early paper models, and work-like [23], such as the suspension module, were utilised. Parts and modules were mostly focused to see if the individual sections functioned as intended before the most optimal were integrated into the final prototype. The final prototype ended up being the most comprehensive prototype with the highest fidelity, although of a medium fidelity and medium resolution compared to an eventual final product ready for manufacturing.

2.4 Prototype testing

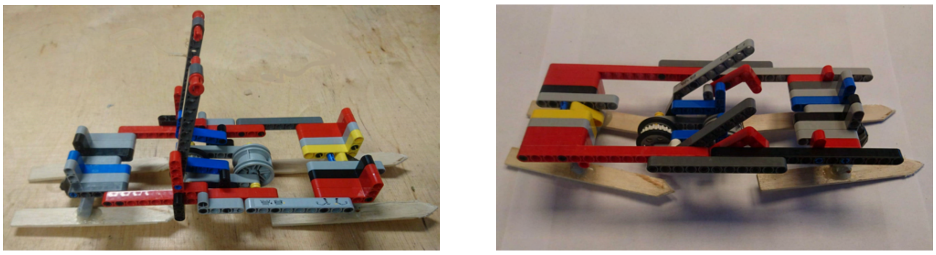
Prototypes where continuously tested in the workshop for their function as quickly as possible to learn as fast as possible, and thereby iterate as fast as possible. The hunter-gather way-fairing approach [18] was applied to a great extent, resulting in the prototyping and prototype testing phase being conducted concurrently. The final prototype was more thoroughly tested in cross country ski trails at Granåsen in Trondheim at the end of the project. Through the testing, valuable insight into successful aspects of the design or improvements were confirmed or revealed.

3 Prototyping process

In the prototyping phase simple low resolution models where initially constructed, followed by more refined and focused prototypes. In the end a final prototype was developed based on the most optimal prototypes of each module. First, low resolution models in Lego and paper where constructed, primarily to test out concepts and theoretical ideas and to learn about the design domain. This was followed by mostly full size models and prototypes of specific modules, such as the suspension module and the height adjustment module. These ranged from focused to comprehensive prototypes, with increasing fidelity.

3.1 Concept modelling with Lego

Lego modeling was utilised at an early stage in the project to further develop the theoretical concepts. Primarily the two functions of steering and suspension with height adjustment were investigated with the prototypes. Figure 9a shows a Lego model with four skis and a height adjustment lever mechanism. In this model the motor section (gray wheels) was only connected to the lever arm mechanism though two connection points. This created a pivot point intended to simplify the construction. Concerns about the possible uneven pressure distribution from the belt to the ground because of this pivot point connection resulted in a second Lego model to solve this possible issue. Figure 9b shows the second Lego model with turning skis and a modified connection between the lever arm and the motor module. The four connection points linked the two modules together, hindering the pivot of the motor module. The height adjustment mechanism proved promising. Both models were constructed with the same steering mechanism. By tilting the chassis the skis turned in the same way a skateboard turns [3]. The mechanism for steering was tested and proved promising.



(a) Lego model 1

(b) Lego model 2

Figure 9: Examples of early stage Lego model prototypes.

3.2 Small size paper model of concept

A small size paper model was constructed concurrently with the Lego prototypes to increase the prototype fidelity and resolution. The first version was roughly 400mm long. A second and shorter version shown in Figure 10 was roughly 300mm long and consisted of a paper chassis, four skis, a height adjustment mechanism and a seat. Unlike the Lego prototypes, this model did not incorporate a functioning turning mechanism. However, the pivot point issue with the height adjustment mechanism was discovered with this paper model. When the force from the belt was transferred to the ground through propulsion or braking, the momentum created though the point connecting the motor module and height adjustment module would result in a pivot. This pivot resulted in an uneven pressure distribution between the motor module and the ground. The second Lego model incorporated a modified connection to accommodate this issue. The small size paper model proved important in visualising the concept of four skis for turning, the height adjustment mechanism, chassis construction and sitting position.

Figure 10: Small size paper model with chassis, four skis, height adjustment mechanism and seat.

3.3 Full size paper model of chassis

To learn more about the construction of the chassis and the general design domain, a fill size paper model was created. This prototype gave insight into the size of the chassis and the possibilities of where to place the seat and general sitting position as well as the space available for the motor and height adjustment module. Figure 11 shows a sketch of the proposed chassis with dimensions to accommodate the size of a motor module and skis. At this stage skis of 87cm were found to be the shortest mass produced skis [9] and the chassis was designed with this in mind. Because of the increased wear on skis used on CCSSs, these skis could be changed when worn out or damaged and were thought to be most ideal. However, later on in the project additive manufactured skis which were only 30 to 40 cm long were used instead. Additive manufactured skis allows for shorter skis and better customiseability in the development process.

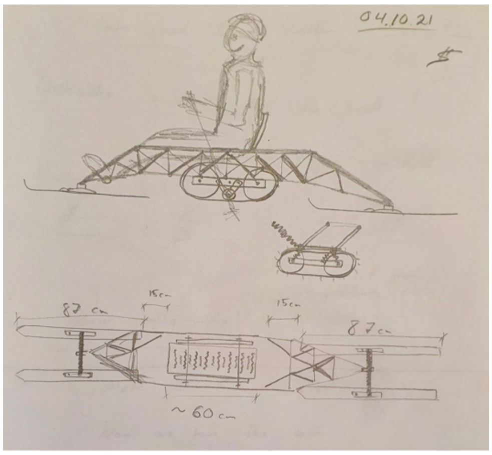


Figure 11: Sketch of full size paper model with important dimensions in cm.

The full size paper model shown in Figure 12 was constructed as a truss structure using rolled A4 paper and tape. The design was inspired by truss bridges, but on this model the chassis ended in single points on each end. This was to accommodate steering possibilities. The first version of the chassis had longer ”legs” and a wider span from the front support point to the to rear support point. To test the sitting position and get a feel for the size and form of the chassis, a chair was used to sit on. The chair was placed beside and inside the paper model, giving feedback about the sitting position without constructing a rigid chassis in for instance steel. This saved a lot of time and resources, while still providing necessary new knowledge about the design. The design and dimensions of the chassis proved promising and a wood chassis was therefore constructed.

Figure 12: Full size paper model of chassis with user sitting on chair behind to test sitting position and general form.

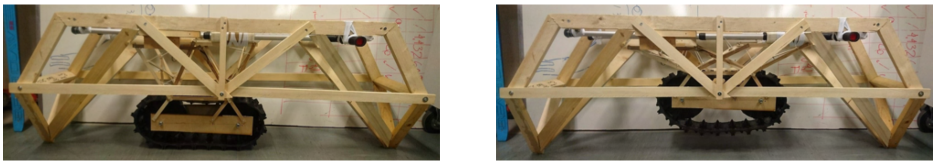
3.4 Wood model of chassis

Using the dimensions and knowledge gained from assembling the full size paper model a wood chassis was constructed. The wood prototype was roughly the same length, width and height as the paper model. To save construction time and material and better accommodate anticipated forces the truss structure was altered slightly. Figure 13 shows the wood model of the chassis constructed with wood and screws. Inside the chassis an early version of the suspension module with belt and wheels can be seen. This wood chassis would later be used to mount and integrate the different modules of the CCSS. The frame strength was tested by sitting on it and applying loads from the top at different angles to verify that it would be strong enough to be used as test chassis in further testing.

Figure 13: Full size wood chassis frame prototype.

3.5 Suspension mock-up with belt and wheels

A simple suspension prototype was constructed based on the theoretical concepts and the knowledge gained from the early prototype building. Much inspiration was taken from snow mobile track suspension, ATV add-on tracks, airplane landing gear, collapsible ambulance stretchers and mountain bike suspension mechanisms. Figure 14 shows the initial suspension mock-up module integrated on the chassis. It consisted of two plates connecting the two axles holding the wheels in place. The wheels and belt track were from a snowblower. Six short members, resembling springs, connected the plates to two horizontal members. These horizontal members were connected to a suspension frame structure allowing for height adjustments. This is further discussed in Section 3.8. The mock-up suspension prototype worked as proof of concept and produced valuable knowledge about the design. Firstly, issues with the stability of the motor module were discovered. The current connection with the short members would create an instability where the motor module would be able to twist or lean to one side. Secondly, this suspension module could be further improved to allow for better movement and surface contact over uneven ground, especially when leaning the chassis when turning. Lastly, the importance of belt tension was highlighted. These issues were largely solved with the next version prototype discussed in Section 3.6.

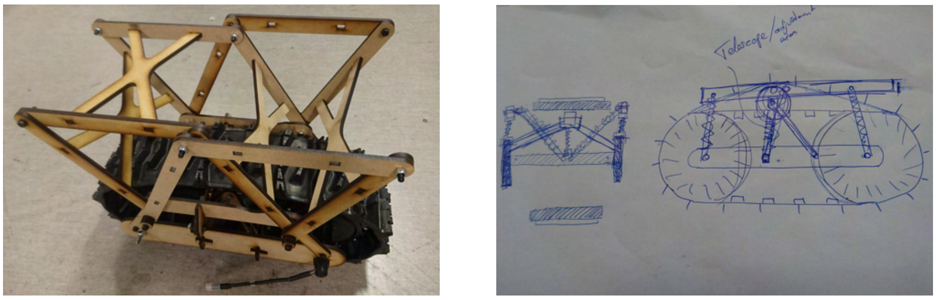


(a) Suspension mock-up module in lowest position (b) Suspension mock-up module in high position

Figure 14: The suspension mock-up module with belt and wheels mounted on the wood chassis.

3.6 Suspension prototype in laser cut MDF

Based on the first suspension prototype, a second version was constructed in primarily medium-density fiberboard (MDF). The design was first sketched and modeled using computer-aided design (CAD) and then laser cut in MDF and assembled with an electric motor inside and a belt tension wheel. Figure 15a shows the prototype of the suspension module. Figure 15b shows a sketch of the suspension with structural members and belt tension mechanism visualised. The belt tension wheel, Figure 15c, was made using additive manufacturing. The mechanism allowed for the adjustment belt tension by regulating the position of two slotted members relative to two tightening bolts. Through in lab testing the belt tension mechanism seemed to work as intended and without issues. Furthermore, an electric motor, discussed in Section 3.7, replaced one of the plastic wheels from the previous suspension prototype, see Figure 15d. Other significant differences between this prototype and the previous suspension prototype included a more rigid structure with more accurately manufactured parts and a different spring suspension setup. More specifically, the integration of members resembling springs linking the upper horizontal members and an inner member connected to the two side plates where the axles were mounted.



(a) Suspension setup in laser cut MDF (b) Sketch of the suspension with belt tension mechanism

(c) Belt tension mechanism with wheel inside suspension module (d) Suspension module with electric motor integrated

Figure 15: Suspension prototype in laser cut MDF.

3.7 Electric motor drive system and integration into suspension prototype.

Electric drive system

The drive system used in this project was an electric battery driven bicycle hub motor controlled through a wired control unit. The motor, shown in Figure 16a, was a geared rear hub DC motor or the type Bafang RM G040.250.D with 36 Volts and 250 Watts power output. The maximum torque and rotational speed were stated to be 45 Nm and 310 RPM respectively. The battery, shown in Figure 16b, was a Shanshan Hailong Battery case with 52 Samsung-29E 18650 rechargeable Lithium battery cells with the following specifics: 36 Voltage output, 14.5 Ah, 522 Wh Power capacity. The weight of the motor was 3.1 kg and the weight of the battery was 3.4 kg. The motor speed was regulated with a thumb throttle on the motor control unit. In addition to the thumb throttle, the control unit also included a control panel and a control unit screen. The control panel was used to switch the drive system ON and OFF, and the control unit screen showed the speed of the motor adjusted for a 26” bicycle wheel. [1]

(a) Bafang RM G040.250.D 36V 250W electric bicycle hub motor

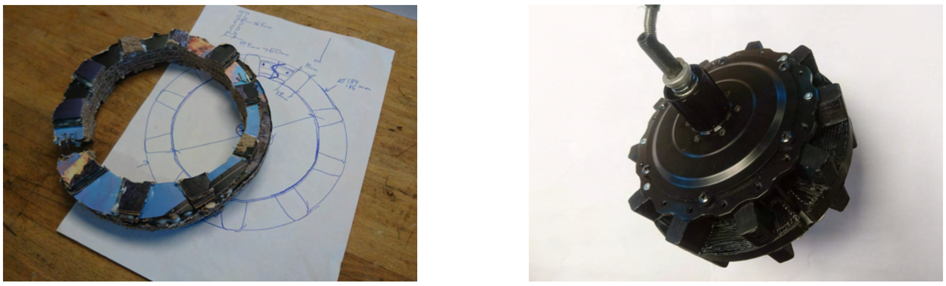
(b) Battery with wiring and motor control unit

Figure 16: Electric drive system with Figure 16a showing motor and Figure 16b showing battery and control units with battery in top left, motor control unit with control panel and screen in centre and thumb throttle for speed regulation in bottom right.

Source: [1]

Cogwheel design and construction

A cogwheel was designed and mounted on the outside of the motor to ensure proper power transfer from the motor to the belt. The cogwheel dimensions were taken from the plastic snow blower wheels used in the initial suspension mock-up prototype. To facilitate a good gear meshing, the same pitch and outer diameter and number of teeth was used for the cogwheels made for the electric motor. First a cardboard cogwheel was created to test how a cogwheel might be mounted on the motor. Mounted on the motor, the cardboard version also provided valuable insight into how the electric motor cogwheel would mesh with the belt teeth during rotation. Figure 17a shows the cardboard cogwheel prototype without hub motor on top of a drawing with cogwheel dimensions. Based on the cardboard prototype, the cogwheel teeth were widened to increase the contact area between belt teeth and cogwheel teeth. Finally, a cogwheel was designed in CAD and produced in two pieces using additive manufacturing. The two parts of the cogwheel mounted on the electric hub motor is shown in Figure 17b, visualising a small gap between the two parts of the cogwheel. However, this gap did not seem to influence the gear meshing.



(a) Cardboard cogwheel prototype and reference drawing of cogwheel dimensions (b) Electric motor with cogwheel made using additive manufacturing

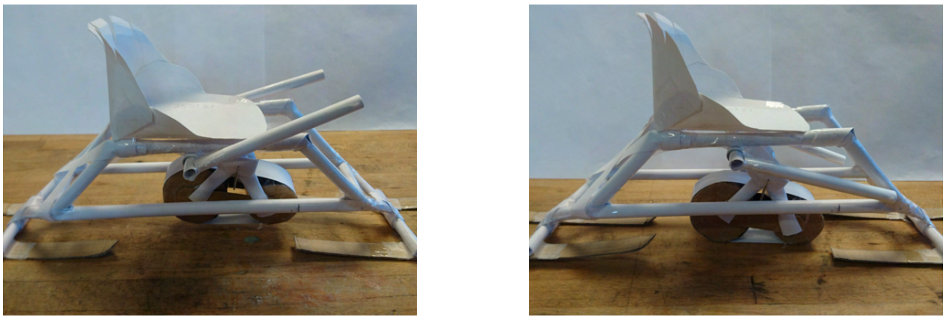
Figure 17: Electric motor cogwheel prototypes

3.8 Height adjustment of belt and motor module

A height adjustment mechanism to raise and lower the motor and belt was implemented in the design of the CCSS. This was done to enable the belt to be lifted out of contact with the ground if necessary. This could be the case on long flat parts of ski trails to for example save electricity or in the case of a flat battery. To make the system as simple and fail proof as possible, e.g. not dependant on electricity, a mechanical manually operated system was desired. Should the user not be able to operate the manual mechanism or want an automatic system, a the system could be altered to facilitate this.

Lever arm mechanism for height adjustment

At first, a height adjustment mechanism controlled manually with a lever was developed and investigated with prototypes. The first small scale paper model and the Lego models described earlier integrated this type of mechanism. The mechanism is explained in Figure 18, with the mechanism in lifted and lowered position. Through further investigation with the full size chassis paper model and the wood chassis prototype, the lever mechanism was found to have several issues. Firstly, the lever arms would be hindering natural poling motion for the user. Secondly, the set up did not create a stiff suspension structure to limit yaw in the motor module. In addition, there would most likely be large forces producing large moments on the horizontal pivot axle requiring thorough stress and strength analysis, possibly resulting in increased weight to handle the forces.



(a) Height adjustment mechanism in lifted position on small scale paper model (b) Height adjustment mechanism in lowered position on small scale paper model

Figure 18: Height adjustment mechanism integrated on small scale paper model.

Turning screw concept for height adjustment

In the light of the knowledge gained with the lever mechanism prototypes, a suspension frame concept was developed to be implemented for height adjustment. Figure 19 shows some of the frame structure concepts. Top left (1) shows a mechanism where a turning screw is used to raise and lower the module. On the right (2) shows how the mechanism easily could be altered by implementing a motor or actuator to accommodate automatic operation. Bottom left (3) shows a gear mechanism to move the frame to raise and lower the module. Although promising, these concepts where not continued because they did not sufficiently solve the issues with yaw and frame stiffness previously discussed.

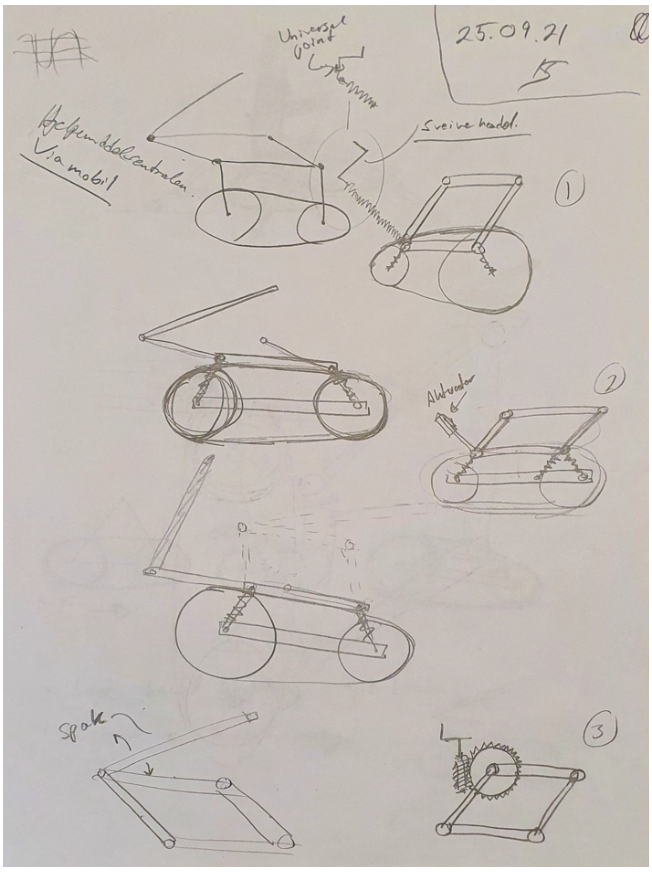


Figure 19: Sketches of concepts for height adjustment module.

Sliding mechanism concept for height adjustment

To stiffen the height adjustment and suspension frame and avoid yaw a new concept with a double frame was developed. A sketch of the developed concept with a sliding mechanism is shown in Figure 20. The mechanism works by sliding the top left part of the structure along a straight and smooth member to raise or lower the motor module. Holes in the straight member allowed the mechanism to be locked in several positions. On the bottom and right side of the sketch a lever handle is shown. This was designed to be used to engage the locking mechanism.

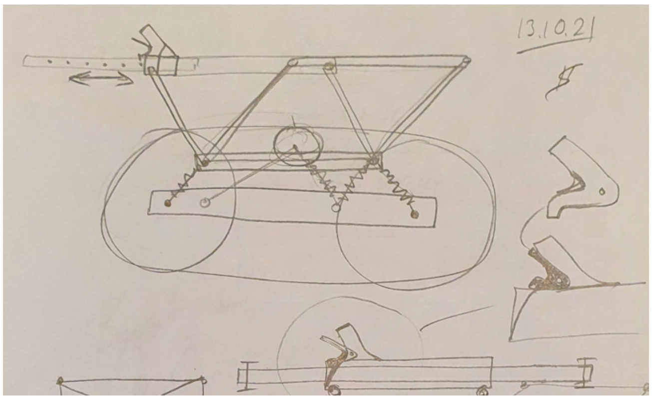
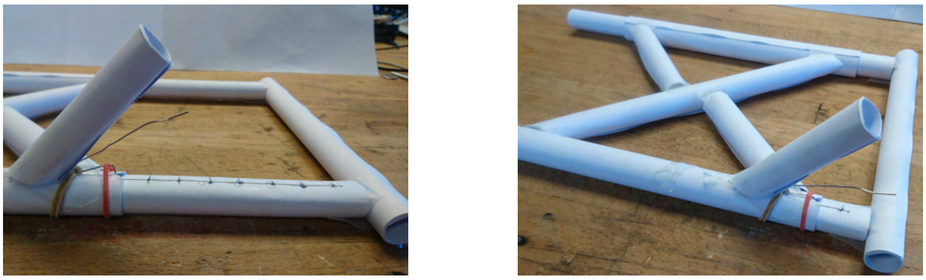


Figure 20: Sketch of a sliding mechanism for height adjustment module.

Based on the concept sketches a paper prototype was constructed to test the functions. Figure 21 shows the paper prototype of the sliding mechanism with a paperclip and rubber bands used for the lever handle mechanism. With holes in the paper cylinder, the lever handle mechanism locked the sliding movement of the structure. This concept seemed very promising and more rigid prototype was therefore developed to test the concept combined with other parts and functions on the wood chassis prototype.



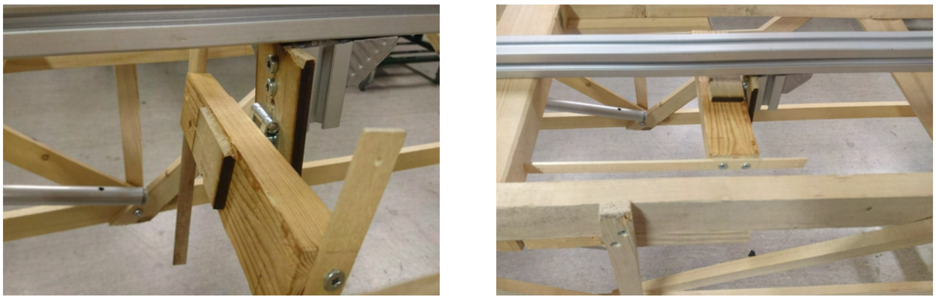
(a) The sliding mechanism paper prototype in paper elongated

(b) The sliding mechanism paper prototype in paper in compact position

Figure 21: The sliding mechanism prototype with simple lever handle and holes in member.

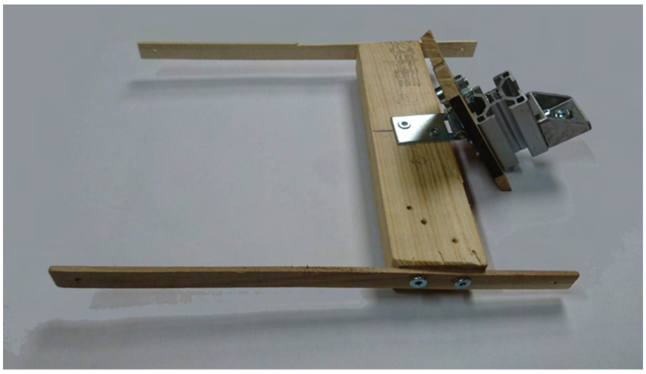
Sliding mechanism with aluminium rails for height adjustment

Before the construction of an more rigid prototype of the previously mentioned sliding mechanism, aluminium rails were discovered and tested for their possible use. A sliding mechanism with aluminium rails was constructed, shown in Figure 22. The prototype configuration with aluminium rails worked by sliding a locking piece inside a long slot in the aluminium rail. The locking piece could be fastened to inhibit sliding motion by tightening a bolt. Although the setup worked well and the long aluminium rail could be integrated as a load carrying structure in the chassis, there were issues regarding the operation. The mechanism for locking and sliding the locking piece along the aluminium rail was difficult to operate because it required a hex key. Furthermore, the locking piece fell out of the aluminium rail slot several times resulting in the whole prototype dividing in two. The aluminium rails were therefore not continued, but instead the knowledge gained noted for the possible reuse and reintegration of the aluminium rails in a future chassis.



(a) Sliding mechanism with aluminium rails in lower position

(b) Sliding mechanism with aluminium rails in raised position on wood chassis

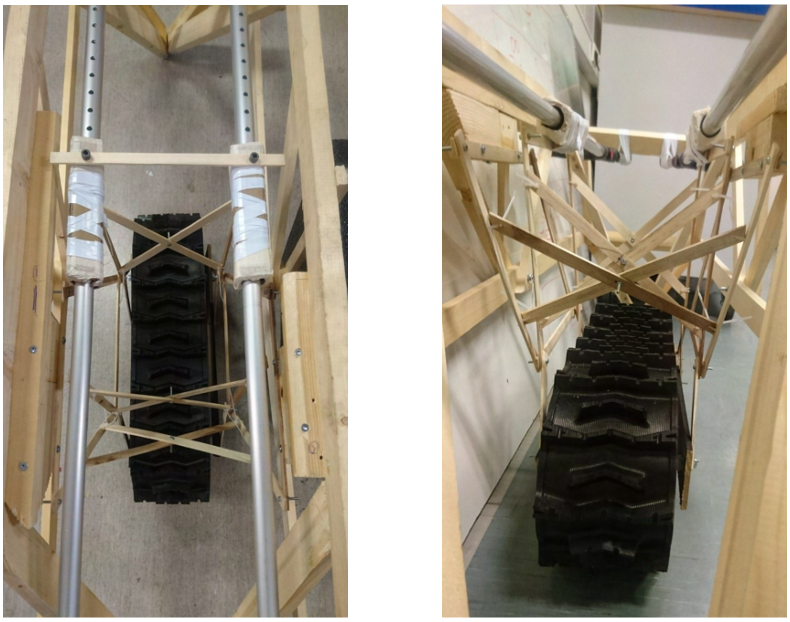


(c) Sliding mechanism isolated without aluminium rail on wood chassis

Figure 22: Height adjustment concept prototype with aluminium rails.

Sliding mechanism prototype for height adjustment with crutches, cardboard and wood sticks

Continuing the sliding mechanism concept tested with the paper and paperclip prototype previously discussed, a prototype was constructed with crutches, cardboard and wood sticks. The prototype integrated on the wood chassis is shown in Figure 23. The crutches are connected to the chassis in front and rear. Two cardboard boxes with holes are mounted round the crutches and slide along them. Bolts are used to lock the cardboard boxes in positions along the crutches. The suspension frame connecting the belt and motor module to the chassis is connected both to the chassis and the cardboard boxes. By sliding the boxes along the crutches, the belt and motor module is raised or lowered. The frame with diagonal cross members limit the sideways movement of the belt, only enabling up and down movement. Yaw motion in this suspension frame is also limited with this construction.



(a) Sliding mechanism for height adjustment with cardboard and crutches mounted on wood chassis, top view

(b) Sliding mechanism for height adjustment with cardboard and crutches mounted on wood chassis, inside view

Figure 23: Sliding mechanism for height adjustment using crutches, cardboard and wood sticks integrated on wood chassis.

3.9 Steering module

Steering capabilities was one of the most important features wanted to be implemented into a CCSS, and therefore a steering module was developed and constructed. Inspiration was taken from the Exero Spike [20], Beitoskilator [2] and skateboard trucks in the design of the steering module. In the design process of the steering module a similar version of the steering module used on the Exero Spike was supplied by Exero Technologies and integrated on the chassis. It was a steering module with axles meant to be used with wheels.

Fixed wood module

Initially, the chassis design was adjusted and the steering modules mounted on the front and rear. Figure 24 shows the steering module mounted on the chassis. Wood was cut out to angle the steering module correctly. The steering module angle of the Exero Spike [20] was used as reference. Through initial lab tests the connections between the wood parts of the steering modules were not stiff enough, resulting in play. even though the steering module did work for steering, This meant that the steering module did not function properly and with less movement than necessary.

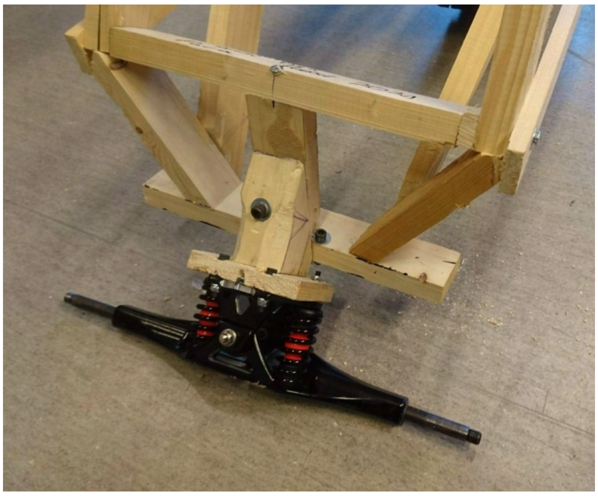


Figure 24: Steering module mounted on chassis.

Adjustable aluminium rail module

To solve the problem with the unwanted play between the wood parts of the steering module other possible solutions were investigated. A new adjustable steering module was constructed using a metal joint that could be locked and an aluminium rail. This adjustable set up, shown in Figure 25, enabled different angles for the steering module. The different angles could potentially be used to adjust the sensitivity of the steering to accommodate individual user needs. Initial tests of the adjustable steering module were promising, but when mounted on the chassis and higher loads where applied, the metal joint was not strong enough to handle the forces. The joint worked as a hinge at higher loads and could not be used to transfer the necessary loads. This adjustable set up with aluminium rail and metal joint was therefore not continued.

(a) Adjustable steering module higher angle setting

(b) Adjustable steering module lower angle setting

Figure 25: Steering module with adjustable aluminium rail and joint.

4 Final prototype

The final prototype was built up of improved prototypes of the ones discussed in the previous section, in addition to a seat. The final prototype CCSS, Figure 26, was measured to be 170 cm from front to rear without skis and 203 cm with skis. The widest part of the CCSS was the seat at 38 cm, which was mounted 60 cm above the ground. At the highest possible setting the belt had a 5 cm clearance to the ground. The final prototype CCSS can be divided into 6 sections: Chassis and sitting position, Steering module, Height adjustment module, Suspension module, Battery and wiring, and Motor control. Each of the sections are explained further in individual subsections below.

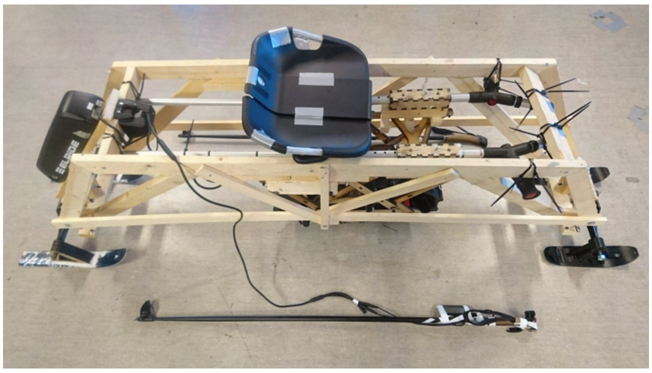


Figure 26: Final prototype in lab.

4.1 Chassis and sitting position

The wood chassis was the structure used to mount all the sections on, as well as the structure that created the sitting position. On top of the chassis a seat was mounted. The seat was of the same type used on the Exero Spike Snow [21]. The seat could be moved back and forth on the chassis. The legs rested on the chassis. The final prototype with a user in a lab is shown in Figure 27. By moving forward on the chassis, the feet could rest on the lower horizontal member at the front of the chassis. An alternative position was to sit with the feet resting where the calves of the user shown in the figure are resting. The sitting position was not surprisingly not the most comfortable, as the main focus of the development project was on other aspects such as the steering module, height adjustment module and motor module.

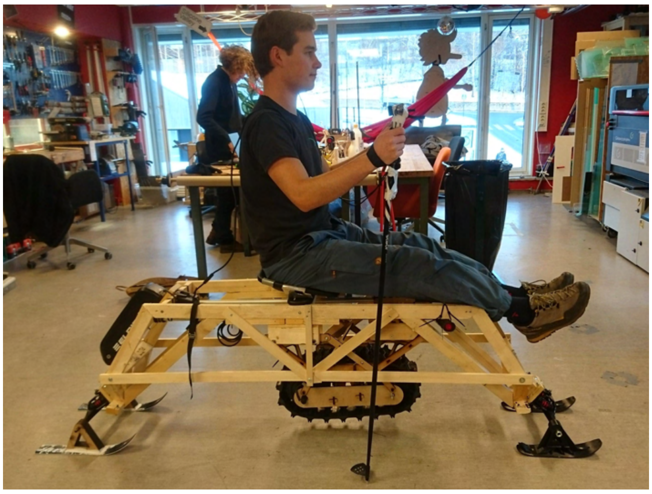


Figure 27: Final prototype with user in lab.

4.2 Steering module

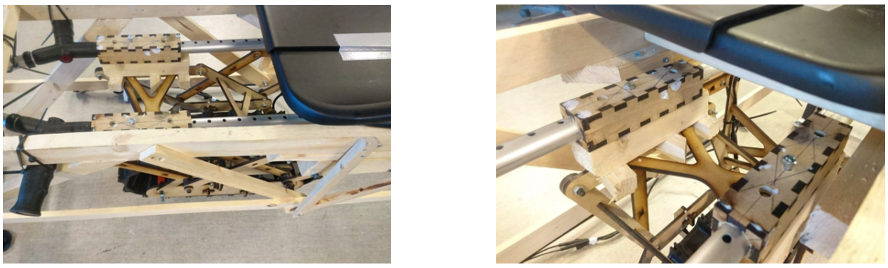
The steering module for the final prototype was an improved version of the fixed wood prototype steering module with skis mounted on the wheel axles. To increase the stiffness and avoid play, the parts were glued together and further reinforced with steel bands and additional screws. The skis used were supplied by SIAT, NTNU. The front pair are additive manufactured in plastic and the rear skis are made from the front part of normal cross country skis with blocks fastened to connect them to the axle. Bolts were used for the front skis and rubber bands were used for the rear skis to avoid the skis from sliding off the axles. The steering modules, front and rear, with skis are shown in Figure 24

(a) Front steering module with skis on final prototype (b) Rear steering module with skis on final prototype

Figure 28: Front and rear steering modules with skis on final prototype.

4.3 Height adjustment module

The height adjustment module installed on the final prototype was an upgraded version of the prototype made with cardboard and crutches. The crutches were firmly and more accurately placed on the chassis. Instead of the cardboard boxes, laser cut MDF boxes were used. The suspension module was connected to the height adjustment module and chassis via custom-made blocks of wood. This resulted in a more rigid structure. M6 bolts through holes in the laser cut MDF boxes and crutches were used as pins to lock the module in specific positions. Raised and lowered positions of the module are shown in Figure 29.

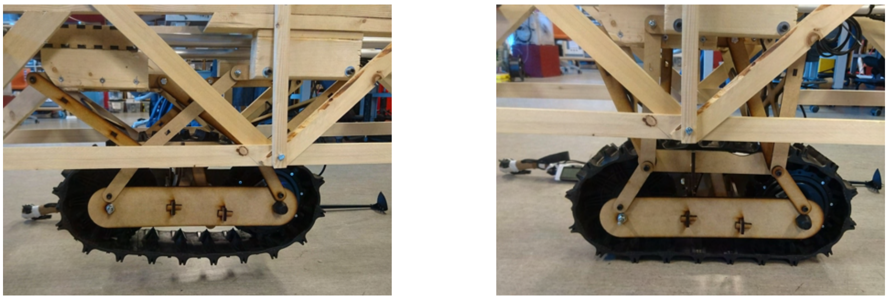


(a) Height adjustment module in raised position on final prototype (b) Height adjustment module in lowered position on final prototype

Figure 29: Height adjustment module on final prototype

4.4 Suspension module

The belt and motor suspension module was mounted on the chassis via the height adjustment module. A wider outer rigger was added on the suspension module, widening the module to make more space for bolts when raising and lowering the module. Figure 30 shows the suspension module in raised and lowered position and how it was mounted to the chassis. The maximum raised position was limited with the front wood blocks connecting the suspension frame to the MDF boxes on the height adjustment module to avoid the belt track lugs from hitting the cross members on the suspension frame.



(a) Suspension module in raised position on final prototype (b) Suspension module in lowered position on final prototype

Figure 30: Suspension module on final prototype.

4.5 Motor control unit mounted on ski pole

To facilitate motor speed control during skiing, the motor control unit was mounted on the right ski pole. Figure 31 shows the right ski pole with the motor control unit attached. At the bottom, the screen was placed showing whether the motor was ON or OFF, the distance and speed adjusted for a 26” wheel and the battery power status. The thumb throttle was placed at the top of the ski pole and controlled using the thumb. Between the screen and thumb throttle the control panel was placed.

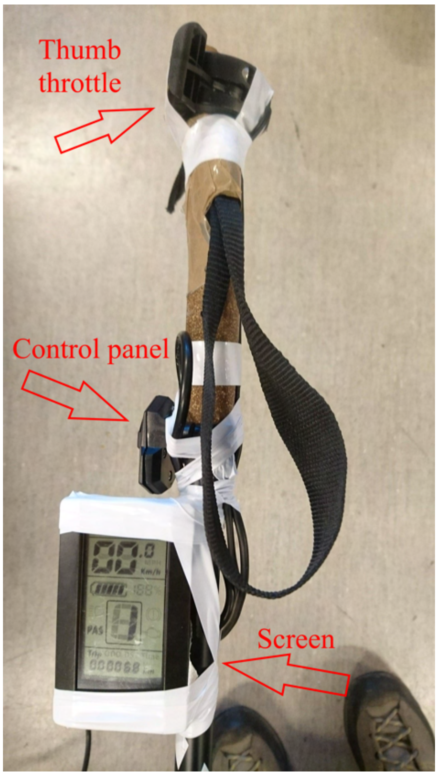


Figure 31: Motor control unit on ski pole.

4.6 Battery and wiring on chassis

The battery was placed at the rear of the chassis to increase the weight at the rear thereby improving the weight distribution on the skis to be more even. Figure 32 shows the battery mounted on the rear of the chassis. Cables between the motor and battery were attached to the chassis using strips. The cables from the battery to the control unit on the ski pole was lose to allow for free arm movement. A strap was used to fasten the cable to the overarm of the user to keep the cable out of the way and avoid it getting caught in e.g. the belt or other moving objects. On the cable between the battery and the motor control unit there was a link working like a safety mechanism. In case the user fell of the CCSS, the cable would detach at the link, turning the motor OFF. Furthermore, the battery was placed in such a way that it could easily be removed to charge disconnected from the chassis and to reduce the weight of the CCSS when in transport.

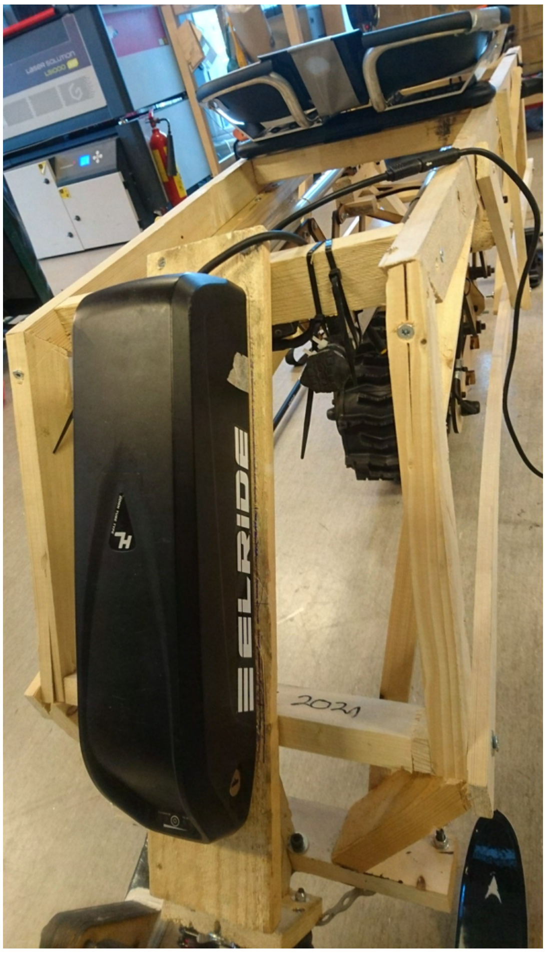


Figure 32: Battery mounted at the rear of the chassis with cables attached to chassis.

5 Testing and discussion of final prototype

The final prototype was tested in a cross country ski trail at Granåsen in Trondheim. Three participants tested the CCSS prototype. One of the participants also logged some of the testing using a GPS watch and a heart rate monitor chest strap to collect data. The CCSS was tested in the following scenarios: Flat ground, up and down a 5°hill, up and down a steep slope approximately 10°-15°, in classic ski tracks and in right and left turns. The conditions where good, with an air temperature of -3°C and fairly compact snow. The trail seemed to have been used a little since it was groomed.

Flat ground test

First the CCSS prototype was tested with belt in raised position by double poling. The CCSS felt quite heavy to move with no propulsion assistance from the motor. The user was not fastened to the seat with a strap and had to rely on gravity to avoid exiting the sitting position while double poling. When the user managed to get up to some speed, the double poling felt easier and the CCSS maintained a steady speed. Additionally, the CCSS turned slightly to the right when the user sat in neutral position.

Secondly, the CCSS was tested on flat ground with belt lowered. The height setting with 6 holes visible on the crutches was used to gain good traction. It was extremely difficult to move the CCSS by double poling without any assistance from the motor because the motor module worked like a brake. However, with the motor propulsion assistance, the CCSS quickly gained speed. No additional double poling was necessary to make the CCSS move. With maximum motor power and double poling the CCSS reached speeds of roughly 10 km/h. Figure 33 shows the testing on flat ground with motor propulsion and double poling.

Figure 33: Double poling with motor propulsion on flat ground.

Uphill and downhill 5°slope

In the second scenario the CCSS was tested up and down a 5°hill with the belt module lowered. The height setting with 6 holes visible on the crutches was used to gain good traction. First, the user was double poling in combination with propulsion assistance from the motor. Ascending the hill was no problem and the the user was not exhausted at the top. On the descent of the hill, the motor provided controlled braking and the user could easily control the desired speed with the use of the thumb throttle. Figure 34 shows the CCSS tested by user down a small slope. In a second ascent, the user was not double poling and relied only on the propulsion from the motor to get up the hill. The CCSS managed to climb steadily up the hill, only stopping once because the belt spun for some unknown reason.

(a) User double poling with motor propulsion assistance on flat ground before small slope

(b) CCSS with user leaning to the left to maintain straight forward travel down small slope

(c) CCSS with user in descent down small slope

(d) At the bottom of the small slope the user was leaning to the left to steer the CCSS straight forward

Figure 34: CCSS tested down small slope with belt lowered for braking and to control speed.

Uphill and downhill steep slope approximately 10°-15°

Furthermore, the CCSS prototype was tested in a steep slope approximately 10°-15°with the belt in lowered position. The height setting with 7 holes visible on the crutches was used to gain good traction. Downhill the motor managed to brake and fully stop the CCSS without problems. The descent felt safe and controlled. Afterwards, an attempt was made to ascend the same hill with double poling and propulsion assistance from the motor. With maximum motor power the CCSS just barely managed to climb the hill. Figure 35 shows the user double poling up the steep hill with motor propulsion assistance. However, due to snow conditions varying from compact to loose the belt track spun several times and had to be lifted past the loose snow patch. The double poling was very exhausting.

Figure 35: Double poling with motor propulsion up steep hill.

In classic ski tracks

Later, the CCSS was tested in the classic ski tracks with the belt in lowered position. The height setting with 5 holes visible on the crutches was used in the classic ski tracks to gain good traction. Both when using only the propulsion from the motor and when in combination with double pooling, the CCSS worked well in the classic ski tracks. However the skis were placed roughly 5-10 cm too far apart for both skis to properly fit in the classic ski tracks. Furthermore, the belt left a mark on the middle of the classic ski tracks. Further investigations in a variety of snow conditions are needed to assess the potential damage to the middle of the classic ski track as a result of the belt pressure.

Left- and right-hand turns

Finally, the CCSS was tested through left- and right-hand turns, with the belt in raised and lowered positions. The CCSS performed well, especially in turning right. Turning left proved more difficult, but it was manageable. In left-hand turns the chassis creaked and seemed less stable. The left ski pole was occasionally used to maintain balance and avoid falling over when turning hard to the left. Furthermore, when turning hard to either side, the rear ski on the opposite side of where the CCSS turned was lifted and lost ground contact. This was especially the case when the user was leaning forward when performing the turn. This resulted in worse turning performance.

5.1 Evaluation of the final prototype in testing

Chassis and sitting position

The chassis was strong and the CCSS felt stable when sitting on it, both in motion and standing still, even though the user sat quite high above the ground compared to conventional CCSSs. The seat worked well for sitting, although the sitting position was not very comfortable. The calves rested on one of the horizontal cross members of the chassis. A belt strap and better leg and foot support could improve the experience. In addition, the sitting position with adjustment possibilities for seat angle and leg and foot position would be desired. Furthermore, the CCSS chassis should be optimized to be lighter, stiffer and stronger to support more load without bending. This is especially relevant when turning hard. With short skis mounted on the CCSS, the chassis can be shortened significantly and thereby saving weight and increasing strength.

Steering module and skis

The steering module worked as intended, although turning slightly to the right when the user sat in a neutral position. This was most likely because the steering module was mounded slightly askew on the chassis or because the wood members on the chassis were in fact not perfectly straight. Figure 36 shows the steering module not mounted perfectly straight on the chassis. By building a more rigid chassis and making sure the steering modules are mounted correctly, this can be avoided in future prototypes.

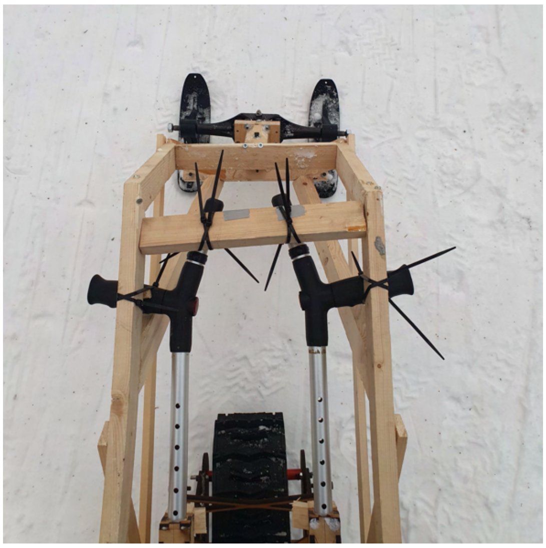


Figure 36: Steering module not mounted perfectly straight on chassis.

In the classic ski tracks both the skis on each steering module did not fit in the tracks at the same time. This can be solved by developing skis that are mounted closer together on the steering modules. However, to enable both the skis to fit in the classic ski track at the same time and ensure high stability with skis placed far apart may seem contradictory. This could possibly be solved by having outrigger skis to maintain balance, while also adjusting the main skis to have the correct distance to fit in the classic ski tracks. Future research is needed to evaluate whether outrigger skis are necessary to maintain balance and a steady CCSS, or whether this can be solved by for instance lowering the centre of gravity.

Height adjustment module

The height adjustment mechanism worked well to adjust the height during testing. However, a better mechanism should be developed because the user had to step out of the CCSS every time the height of the belt module was adjusted. This can be avoided if the lever to operate the height adjustment mechanism is more accessible for the user. Furthermore, the mid point on the crutches where the suspension module was connected bent slightly upwards when the motor accelerated. This was due to the increased forces applied to the crutches through the suspension frame members during loads on the motor. The result of the bending was a reduced ground pressure between the belt and the ground. This did not seem to greatly affect the traction, but might however have played a role when the belt track lost traction up the hills.

Suspension module

The suspension module worked surprisingly well, given that it it was constructed primarily using laser cut MDF plates. During the testing, however, one of the members in the suspension module broke. This is shown in Figure 37. This did not greatly affect the function of the suspension module, but resulted in a less stiff structure and in some situations less even pressure distribution between the belt track and the ground. Furthermore, during high loads on the motor, the motor axle twisted and as a result disconnected the power resulting in a motor stop. This happened because the motor axle was mounted to MDF plates with a locking grove to avoid axle spin that did not support the high loads. Future versions should be designed with this in mind.

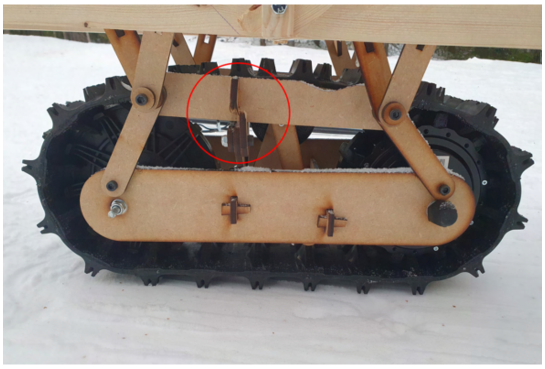


Figure 37: Broken part on suspension module during testing.

During belt rotation the cogwheel seemed to sometimes mesh badly with the belt teeth. This was maybe because of the screws and metal plates used to connect the two parts of the motor cogwheel. Other reasons for the sometimes bad meshing may be a result of a slightly larger distance between the teeth of the motor cogwheel across the connection point compared to the distance between the rest of the teeth. Figure 38 shows the connection of the two motor cogwheels and a gap between the two cogwheel parts. Future versions of the motor cogwheel should take this into account.

Figure 38: Connection of the two motor cogwheel parts.

Motor and motor control

During the testing the motor performed well, showing no signs of overheating or development of heat. This was controlled and measured by touching the motor casing to feel the temperature. The motor seemed to supply adequate amounts of propulsion assistance during testing. To ensure even and reliable propulsion assistance during operation a better suspension system should be prioritised over a more powerful motor.

The motor control worked well during the test, even though improvements to the motor speed regulation would ensure a more comfortable and user-friendly operation. While wearing thin gloves the thumb throttle was quite easy to regulate. On the other hand, when wearing mittens the thumb regulation proved more difficult. The thumb throttle also required fine and accurate muscle movements in the thumb to operate. The ON and OFF button on the control panel was easy to operate, but the screen was difficult to use. This was especially the case when double poling, as the screen was attached to the ski pole. On a final note, the cable between the battery and the control unit on the ski pole did not get caught by any of the moving parts and was not in the way during double poling. However, the strap used to was necessary and attention was needed to make sure the cable was in an OK position during double poling. A wireless connection between the control unit and the battery and motor or better and easier cable attachment to the user instead of a simple arm strap could solve this issue.

5.2 Feedback from test participants

The test participants were impressed with the prototype, but also supplied some points of improvement. Firstly, the test participants noted that the CCSS prototype felt stable and sturdy even though it was quite high compared to other conventional CCSSs. Secondly, the test participants felt safe sitting on the CCSS, as long as the belt was in contact with the ground because the motor module provided propulsion and braking assistance. Thirdly, the test participants remarked that the steering worked well, although the CCSS turned slightly to the right when sitting in neutral position. Furthermore, the test participants noted that the sitting position was not very comfortable. The top horizontal member at the front of the chassis was in the way, hindering a more comfortable sitting position. The sitting was not bespoke to the individual test participants, resulting in a less comfortable experience. The test participants wore different gloves and mittens and ,another comment regarded the motor control. Although the thumb throttle worked and was easy to use, there were some issues in fine tuning the speed while skiing. This was especially the case when using thick mittens. The test participants indicated that the CCSS prototype was heavy when double poling without motor propulsion. Finally, the test participants mentioned that the CCSS could be lighter and easier to transport.

5.3 Evaluation of the engineering development approach

Overall, the project development approach was successful measured by the output of the project. A successful prototype was developed and tested, producing valuable knowledge for future design development. In retrospect it often seems easy to judge the decisions taken, but it is important to remember that the decisions were taken without all the knowledge that was gained to the end of the project. By using a set-based approach [23] [11] in combination with the hunter-gather way-fairing approach [18], the prototypes were continuously adjusted according to the user needs and the new knowledge gained throughout the project. This increased the chances of developing a well functioning prototype that met the product requirements. Because the final requirements in this project were discovered trough prototype testing the approach used was advantageous. If a more traditional engineering approach, implementing e.g. stage-gate or waterfall model [4], had been followed a final prototype could perhaps have been developed in a shorter amount of time. However, this would most likely not have yielded the same successful results because agile iterations would not have been implemented or valued to the same degree. As a result knowledge would be gained slower or not at all during the development before the final prototype was constructed. Only then would the prototype be tested, knowledge gained and the prototype changed based on the findings.

6 Further work

The developed CCSS prototype can be improved in several ways to better accommodate the user needs and give a better user experience. In the subsections below recommendations for further work related to the future development are presented.

6.1 Chassis and sitting position

The chassis construction can be improved by shortening the distance between the front and rear skis. This may solve the issue with unequal force distribution on the skis during turning. Furthermore, other materials than wood and MDF should be utilized to both reduce weight and increase strength and stiffness of the chassis. Materials such as aluminium or steel and composites, as well as 3D printed polymers should be investigated for the chassis frame structure. The possibility to construct the chassis in plastic using additive manufacturing should be looked into. Investigations into different structure types, such as monocoque, space frame or ladder chassis structure is recommended to optimize for weight and stiffness. Finally, the chassis should be designed with transport in mind. Perhaps with the possibility of disassembling the chassis and CCSS in smaller sections to make the transport, especially in cars, easier and lighter to carry.

In addition, the sitting position should be prioritised and integrated in the chassis design to achieve a comfortable sitting position. Straps over hip and legs should be included to fasten the user properly. Better leg and foot supports should be integrated. Back support possibilities should be looked into. A design enabling individual adjustments to each user. Furthermore, the CCSS should be designed to be easy to mount and dismount for a person sitting in a wheel chair. When designing for this aspect, it should be done with great care, as it is a very important feature for increasing the user-friendliness and convenience of the CCSS.

6.2 Steering module

The steering module should be mounted to the chassis in such a way that it is straight and stiff. This will ensure that the CCSS does not turn to one side when the user is sitting in a neutral position. Some users may however have an uneven weight distribution when sitting in a neutral position. This can for instance be the case for amputees or people with cerebral palsy. This may be accounted for with the use of additional counter weights mounted on the chassis to achieve even weight distribution. On the contrary, to avoid increasing the weight, the spring stiffness of the steering module might be adjusted to obtain the same result. Finally, the sensitivity of the steering may be optimized by adjusting both the spring stiffness and the mounting angle of the steering module on the chassis.

6.3 Skis

The skis can be optimized for weight, stiffness and low friction on the snow. Different materials should be investigated. Future versions of the skis should be be optimized for the most suitable length. It might be the case that a longer skis will result in less frictional drag and improve the steering performance. If no other more suitable solution is found, the rear skis should be constructed, like the front skis, using additive manufacturing and incorporate a tip at the rear of the skis to accommodate for reverse CCSS movement.

Furthermore, width adjustment of skis to fit in and outside cross country ski tracks should be implemented. This will enable a more convenient use because the CCSS skis will follow the tracks. However, it is important to mount the skis wide enough to maintain a stable ride on the CCSS, especially when turning. The possibility of integrating side skis to increase the stability should be looked into. This would possibly increase the stability, but also perhaps increase the frictional drag.

6.4 Height adjustment module

The height adjustment mechanism should be further developed to be more ergonomic and user-friendly. The mechanism must be easy and smooth to operate for the user. Investigation into the design of a motor driven height adjustment with the possibility of manual override is recommended. This would, as long as it does not add to much weight, likely create a more enjoyable experience when skiing. Futhermore, the height adjustment module should, if possible, be integrated in the chassis. This will possibly increase the stiffness and reduce the weight. It is important that the module is designed to be stiff enough to avoid bending such as experienced in the crutches on the developed CCSS.

6.5 Suspension module

The suspension module should be manufactured in a stronger material that does not fall apart or change shape when in contact with water. The structure should also be analysed and optimized to reduce stress concentrations and increase the stiffness while also reducing the weight. This is especially important for the parts that were damaged during testing. Investigations into new designs of the suspension module is encouraged. Furthermore, springs and potentially also dampers should be integrated to ensure even pressure distribution between belt track and ground. In addition, further research should investigate whether the belt should be lifted higher above the ground to avoid touching the ground in rough and bumpy terrain when in raised position.

6.6 Electric motor cogwheel

Future versions should investigate whether the electric motor cogwheel should be manufactured in a different material to reduce wear on the parts. The gap between the cogwheel parts around the motor should be minimized in future versions and the connection between the parts should be designed so that the belt teeth is not hit by bolts and screws. The cogwheel structure should furthermore be optimized in strength and reduced in weight if possible.

6.7 Motor control

The motor control can be optimized in a variety of ways. Firstly, the motor control of the CCSS should be modified so that it can not be used like a snow mobile. The user should be required to double pole for the motor to provide propulsion. This can possibly be done by integrating a uniaxial strain gauge load cell. Research into the use of this in ski poles seems promising [10]. In addition, the motor control unit screen should be placed so that it is easier to view during double poling and use of the CCSS. The possibility of a heads up display in glasses or goggles may be worth studying.

The motor speed regulation should be further investigated. The integration of a foot pedal or a thumb throttle mounted differently on the ski pole could be beneficial depending on the user. It if very important that the motor control is user-friendly and safe to use. Furthermore, an automagical speed regulation control should be explored. By regulating the speed depending on the heart-rate of the user or the angle of the ground or slope this may be achieved. Finally, a safety mechanism should be integrated to shut the power OFF in case of an emergency or if the user falls off the CCSS.

7 Conclusion

Conventional cross-country sit-skis available on the market today are valuable equipment to Paralympic cross-country skiers and highly tailored to the user. However, the equipment is difficult to steer, can be demanding and scary downhill and prove exhausting in uphill. Through this project, knowledge was gathered and user needs were mapped before prototypes were developed. Through the prototyping phase design possibilities were explored and knowledge about the construction and needs of a cross-country sit-ski was gained. Based on the work and prototypes a final prototype was constructed. Through testing with three test participants in cross-country ski trails the final prototype was analysed and evaluated for performance and general design.

The final prototype proved highly functional and stable in the tests, however the design would benefit from further improvements. The developed final prototype worked well on flat ground, in left- and right-hand turns, in classic ski tracks and up and down both steep and gentle slopes. The skis were placed to wide to fit properly in the classic ski tracks at the same time and in the steepest slopes the motor had some problems providing enough propulsion due to loss of traction. Other issues discovered through testing include slight turning to the right when user was in a neutral position and even though the height of the seat felt right and stable the sitting position was not comfortable and made powerful double poling challenging. Furthermore, parts of the suspension module constructed in laser cut MDF-plates were damaged during testing due to exposure to higher loads than they could handle. Recommendations for further work include and are not limited to, the design and construction of an improved chassis structure, a more solid steering module mounted straight on the chassis, a strength optimized suspension module with springs, the utilisation of stronger and better materials than wood and MDF-plates and an improved sitting position to increase comfort for the user.

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2022

Master's thesis

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