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Prototyping and Testing During an Assistive Sports Equipment Development Process

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Abstract

An important part of the development process is to validate ideas and concepts continuously. Within physical design, this is primarily done by creating prototypes and testing them. This process is especially important within assistive technology development as the design team rarely can identify with the end-user. Both the prototyping process and the testing can however be performed in countless ways. This thesis aims to answer what method to be used when creating prototypes, and how they should be tested.

Both prototyping and testing methods was tried out on two products under development of the company Exero Technologies. Set-based prototyping, the process of creating set-based prototypes, and rapid prototyping were all methodologies used with different purposes. Several prototypes were created using each method, trying to solve different problems. The processes were then compared trying to answer which to use when.

Each prototype was tested using different testing methodologies and information gathering techniques. The methods, in-house testing, long-term testing, short-term testing, workshops and event testing were all used on different prototypes. These were combined with information gathering techniques like observations, questionnaires, and thinking aloud. The participants consisted of the authors, potential end-users, and care-givers.

The results indicates that each of the methodologies presented are valuable in its own way. The thesis concludes with the advantages of the different methodologies and when they should be applied.

Sammendrag

En viktig del av produktutviklingsprosessen er å kontinuerlig validere ideer og konsepter. Innenfor fysiske produkter gjøres dette først og fremst ved å lage prototyper og teste dem. Denne prosessen er spesielt viktig innen utvikling av hjelpemidler siden ingeniørene sjelden kan sette seg i sluttbrukerens situasjon. Både prototyping og testing av disse kan utføres på mange måter. Denne oppgaven tar for seg hvilke metoder man bør bruke ved utvikling av prototyper og hvordan de burde bli verifisert.

Både prototype- og testmetodene ble utført på to produkter under utvikling av oppstartsselskapet Exero Technologies. "Set-based prototyping", det å lage "set-based prototypes" og "rapid prototyping" var metoder som ble brukt med forskjellige formål. Flere prototyper ble utviklet ved bruk av hver metode, med ønske om å løse ulike problemer. Disse metodene ble deretter sammenlignet opp mot hverandre for å svare på når hver av dem er hensiktsmessige å bruke.

Hver prototype ble testet ved hjelp av forskjellige testmetoder og teknikker for innhenting av informasjon. Metoder som intern testing, langtidstest, enkelttest, workshops og testing på arrangementer, ble brukt på forskjellige prototyper. Disse ble kombinert med teknikker som observasjoner, spørreundersøkelser og diskusjon for innhenting av informasjon. Deltakere i prosjektet har vært forfatterne, potensielle sluttbrukere, deres pårørende og fagpersoner.

Resultatene viser at hver metode er verdifull til hvert sitt formål. Oppgaven avslutter med å presentere fordelene og ulempene ved de ulike metodene og når de burde benyttes.

Preface

This master thesis is written in collaboration with Exero Technologies. The purpose of the master thesis is to give an overview of how prototyping and testing can be used to developing assistive technology. The goal of the project is to inspire the product developers at Exero Technologies, as well as others, to continually make innovations in the field of activity equipment for people with disabilities.

The master thesis is written by two students from two different faculties at NTNU Trondheim. We want to thank our mentors Knut Aasland, Lise Aaboen and Torgeir Aadland for support and advice on the project. It is much appreciated that this project has been made possible as a joint effort between the Department of Mechanical and Industrial Engineering and the School of Entrepreneurship. At last, we want to thank the test subjects for support and feedback during this project.

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Table of Contents

List of Figures

Chapter 1

Introduction

This master thesis is a product development case written for NTNU Department of Mechanical and Industrial Engineering. The authors consist of one student at the NTNU School of Entrepreneurship and one student at NTNU Mechanical Engineering (hereafter the authors).

Based on literature review, experience and research, the authors will identify and describe challenges with prototyping and testing of assistive technology within a hardware start-up. The challenges are presented to the reader by following the development process of two products from the authors' own start-up company. The products represent two different stages in a development process, respectively early and late stage. The project is performed with the aim of developing new products for commercialization and contributing to the research in the field of assistive technology.

1.1 Characteristics of developing assistive sports equipment

Developing assistive sports equipment leads to some difficulties. One of the challenges is that the intended users are a part of a ”vulnerable” group in society. The intended users might have needs and preferences due to their condition, which is impossible for the designer to understand. Regular user contact is therefore crucial during such development processes.

The potential number of disabled users is limited, which affects the manufacturing quantity of the product. Developers of assistive technology devices seek to produce devices that are effective, reliable, satisfying to use, and at the same time cost-effective. This is a big challenge in product development as these goals often contradict one another [1].

1.2 Exero Technologies

Exero Technologies is a start-up company located in Trondheim at the Norwegian University of Science and Technology (NTNU). The company was founded in January 2017 and is developing adaptive sports equipment for poeple with disabilities. Their vision is to give everyone the same possibilities to have an active and happy lifestyle. Exero Technologies consists of five students (including the authors), three from the NTNU School of Entrepreneurship and two from Mechanical Engineering (hereby referred to as ”the team”). The company is now in the process of commercializing their first product and further development of new versions.

1.3 Spike

Exero Technologies is currently developing their first product, called Spike. This is a sled with wheels used for activity by people with disabilities. Figure 1.1 and 1.2 show the current prototype of Spike. The idea of Spike came from a bachelor thesis written for NTNU Centre for Sports Facilities and Technology. It presented a problem that professional paralympic sit-skiers experience today. Sit-skiing is equivalent to Nordic skiing with cross-country skis for non-disabled persons. The athletes within this sport are lacking a good and safe solution for training their sport in the summer season. There were some solutions on the market, but they were not seen as satisfactory by the athletes. Most of them are lacking a functional steering system, and brakes were either missing or unsuitable.

Figure 1.1: Prototype of Exero Spike

Figure 1.2: Bendik Fon using a Prototype of Exero Spike

The three engineers at Exero Technologies developed a solution where the user steer the device by distributing their weight towards one side of the sled, which is unique within these types of equipment. The main components are made of materials like aluminum, ABS plastics, and fabric. Disc brakes were also implemented to make the solution safe. As with sit-skiing, the user propel themselves by using poles (see Figure 1.2). Several versions of the prototype have from January 2017 to May 2018 been tested by 80 potential users. This type of user-oriented product development has resulted in a product that several users have requested leading up to Exero's first sale of a prototype in the spring of 2018. The next goal is to finish development of Spike and start selling in Norway during 2018.

1.4 Spear

During testing with Spike, the authors discovered some limitations with the solution. Based on different disabilities and preferences the sitting position was considered unsuitable for some users. The knee-sitting position excluded some users due to their disability. Some users were unable to bend their knees into the correct position and some experienced difficulties when transferring from a wheelchair to the sled.

Based on these findings and a specific request from a potential user, Exero decided to develop Spear during the pre-masters project (Appendix A). The product, called Spear, was developed with a different sitting position to include those who were not able to use Spike (see Figure 1.3). Steering, brakes, and wheels would be reused from Spike, and the overall design would be developed further.

Figure 1.3: Prototype of Exero Spear from the project thesis

1.5 Social Benefits

The Norwegian Government's Action Plan for persons with disabilities defines disabilities as follows:

> *"A disability is a discrepancy between the capabilities of the individual and the functional demands of his/her environment in areas which are significant for the establishment of independence and a social life"*
> (Regjeringen, 2017)

Being disabled can cause several challenges in everyday life. In Norway, it is a priority for politicians to facilitate work and leisure time for people with disabilities. The following statement is taken from the Norwegian Government website:

> *"The Norwegian government wants to improve living conditions for people with disabilities. Despite being disabled, people should have the opportunity to participate as much as possible in working life and social life. People with different disabilities should have the opportunity to a meaningful free time and to participate in social arenas. The government will take several steps to realize these goals"* (Regjeringen, 2017)

United Nations Human Rights has declared that people with disabilities shall have the possibilities to ensure their human rights and that the society shall enable this [2]. A report from Medtek Norway regarding assistive devices in Norway concludes that there is a need for innovation in this field and that it should be facilitated by new technology [2].

Exero Technologies has so far received a considerable amount of goodwill and support for introducing an activity solution for people with disabilities. Since January 2017 Exero Technologies have raised 1 450 000 NOK from Innovation Norway and Forskningsrådet, in addition, to have won 265 000 NOK in different business competitions. This is the result of the joint effort of a hardworking team and an innovative solution. Feedback from users, the welfare service and existing players in the market indicates a need and place for Exero Technologies.

1.6 Assistive technology

Definition from the World Health Organization's:

> *"Assistive technology enables people to live healthy, productive, independent, and dignified lives, and to participate in education, the labor market and civic life"* (WHO, 2017)

An assistive device is not a goal in itself, and it is not the only means of solving practical problems. The purpose of the assistive device is to compensate for the loss of function and solving practical problems, and they must be seen in conjunction with other forms of help to the user. Assistive devices have a function as long as they solve problems that need to be solved. It is crucial that the users are motivated to use the assistive device. The department of assistive technology in Norway consider a problem solved first when the user is satisfied with the assistive device and how it works [3].

1.7 Research Questions

The purpose of this study is to encourage others to develop new and innovative solutions within assistive technology. This is done by showing research from relevant literature and methods on how prototyping and testing can be used in the product development process.

Exero Technologies has acquired a lot of knowledge in the field of adaptive sports equipment since they started. To evolve and survive as a company it seems necessary to expand the product portfolio and the knowledge concerning product development. This project will focus on discovering which tools and processes within prototyping and testing that fit best with the development of assistive sports equipment. This is done by testing out different prototype methods, then test the prototypes with different test methods and at last evaluating them.

R1: How should prototyping be used when developing assitive devices within a start-up company?

R2: How should testing of prototypes be performed within assistive technology development?

1.8 Scope

This master thesis focuses on different types of prototyping and testing methodologies related to the start-up company Exero Technologies. These methodologies are following two real product development cases, but these are not described in detail in this master thesis. Literature that is considered relevant to give specific recommendations is selected. Data and information regarding Exero Technologies are self-reported. Theory in this field is gathered from search engines for scientific articles and from lectures in the course Advanced Product Development at NTNU fall 2017. This thesis does not include the development process which is performed parallel with this thesis. Instead, the report will present problems or uncertainties discovered in the mentioned process and then describe the prototyping and testing process from problem to results.

The first part of this article reviews theory on the subject. The following part describes how the authors have conducted different methodologies within prototyping and testing. The thesis ends with a discussion and conclusion, with limitations of the study, and suggestions for further work.

Chapter 2

Theory

This chapter consists of literature gathered throughout this master project that is considered relevant to the thesis. Some sections describe specific information regarding assistive devices and uncommon parts. The literature is meant to give the reader a broader understanding and background for the following chapters.

2.1 Mechanism of a truck-system

A ”truck” is usually known in context with skateboards and is the name of the axles where the wheels are attached (see Figure 2.1). Steerable wheeled boards such as skateboards are widely used for sport, recreation, and transportation. Generally, skateboards are steered by the rider shifting his/her weight and causing the skateboard platform to tilt. Steering forces are applied to the wheelsets, typically arranged at opposite ends of the skateboard. The wheelsets are tilted relative to the platform supporting the rider when he/she is shifting his/hers weight from side to side [4].

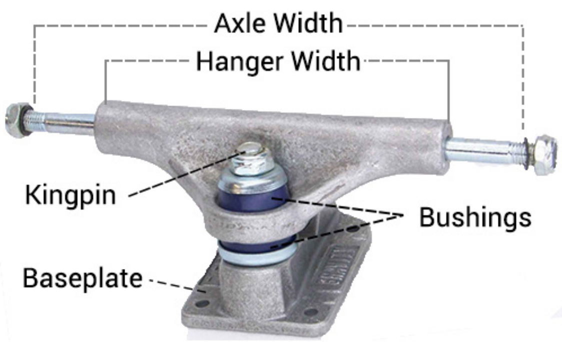


Figure 2.1: Classic skateboard-truck [5]

The trucks used with Spike are attached using a unique suspension system called a channel truck (see Figure 2.2). Channel trucks pivot on a central pin, like a see-saw. This pivoting design offers a broad range of motion. The trucks are cushioned by springs and shock absorbers on both sides of the central pin. This allows for deep, carving turns even at high speeds. One of the benefits of these type of trucks is adjust-ability, with the possibility to wind down the springs and dampeners to increase the resistance.

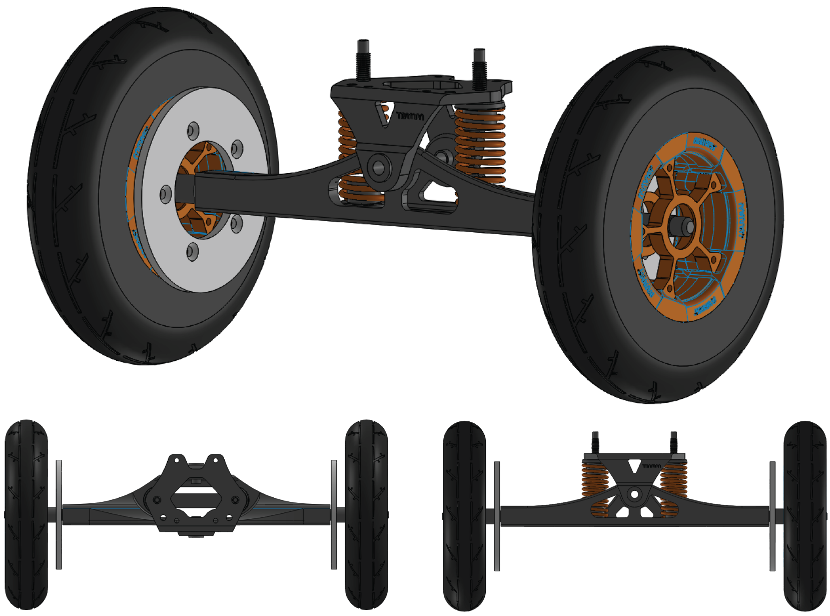


Figure 2.2: 3D representation of the channel truck used on Spike and Spear

2.2 Pressure ulcers and how to avoid them

Pressure ulcers, often referred to as bedsores, are injuries to skin and underlying tissue resulting from prolonged pressure on the skin. Pressure ulcers could be developed on skin that covers bony areas of the body, such as the heels, ankles, hips, and tailbone (see Figure 2.3). People that are themselves not able to change their positions are most prone to develop pressure ulcers. In a sitting posture, the interface pressure is higher than when in a lying posture. The risk of pressure ulcers is therefore significantly increased during long periods in a sitting position. Pressure ulcers can develop quickly, and measures should be taken during developing new equipment to prevent injury on future users [6].

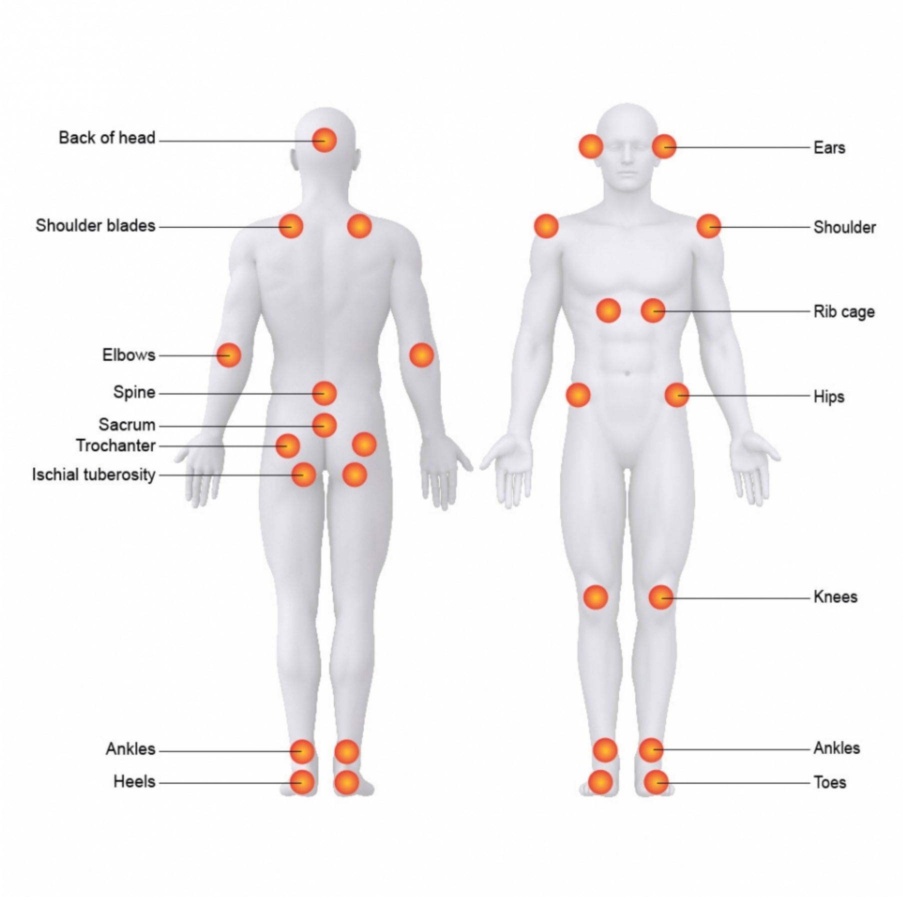


Figure 2.3: Areas prone to develop pressure ulcers [7]

Typically methods to avoid pressure ulcers includes moving and regularly changing positions, and using specially designed cushions that reduce the pressure. Research from Defloor and Grypdonck (1999) concluded that air cushions and slow foam cushions have the best pressure-reducing effects in use of hospital armchairs. According to Reddy *et al.* (2006) the most promising prevention are using appropriate support surfaces (mattress overlays on operating tables, specialized foam overlays, and specialized sheepskin overlays), optimizing nutritional status, and moisturizing sacral skin. They conclude that re-positioning is a mainstay of ulcer prevention, but it is not known whether specific strategies have advantages over others [8].

2.3 User contact

One of the main challenges regarding the development of assistive technology is to find the user requirements. In most cases, designers are dependent on finding users with first-hand experience. A non-disabled designer may have an incomplete understanding of a disabled users abilities and needs. It is even more difficult to understand the implications of what it means to live with functional limitations from day to day [1]. Development of medical devices from users' perspectives requires not only the involvement of healthcare professionals but also end users, e.g., patients, people with disabilities and/or special needs, and their caregivers [9]. The analysis of user requirements is one of the most critical factors for effective special needs developments [10]. According to Bühler (1996), the experiences of long-term users are especially helpful. For instance with new technology prototype testing where users can correct the aims by giving unexpected inputs [10].

User involvement is, on the other hand, associated with a higher resource demand, both in time and money. The resource demand is discussed by Shah *et al.* (2009) where benefits and disadvantages of involving users in medical technology development cases are highlighted [11]. For instance, time and money invested from the manufactures is seen as a critical factor, and there is no guarantee that the outcome of involving users in the development process, will be positive. However, despite the resource demand, it is concluded to be essential for both users and manufacturers perspectives [11].

One way to address the gap between the designer and end-user is through the testing and evaluation of concepts and prototypes. Methods for testing include usability testing, observation, thinking aloud, questionnaires, interviews, and focus groups. These methods can be used alone or combined with each other. Due to the time-sensitivity nature of a development process, the methods must be time efficient, and testing objectives must be clearly defined. Evaluating and comparing the usability of prototypes among end users is also complicated by the need to fabricate prototypes that are representative of the actual design [1].

2.3.1 Usability Testing

A full usability test involves determining what will be measured, recruiting appropriate users, having the users perform typical tasks, and collecting data to be analyzed. The test itself may involve evaluating one or multiple concepts for comparison [12]. The evaluation is often repeated during the design process, from early to late-stage development.

2.3.2 Observations

To fully understand the complexities of different situations, direct participation and observation may be the best research method. The data collection must be descriptive so that the reader can understand what happened and how. In most applied projects, there is not enough time to carry out a detailed observational study, however, some observation will help. Observational data is also instrumental in overcoming the difference between how people describe their actions versus how they actually perform them. This can help to uncover behaviors which participants themselves may not be aware of. Observation makes it easier to understand and capture the context within which participants interact. Firsthand experience with a setting allows researchers to open up to discovery, rather than guessing what the context is. It provides a chance to learn things that people may be unwilling to discuss in an interview [13].

2.3.3 Questionnaires

Questionnaires consist of a series of questions with the purpose of gathering information from the participants. They are effective means of finding subjective preferences and are easy to repeat and compare, but they require pilot work to ensure clarity and reliability [1].

2.3.4 Thinking Aloud

A potential way to gain insight into the test subjects' thought processes, is to ask test subjects to "think aloud." According to Nielsen, this practice plays an important role in usability data collection, and he even goes as far as to say, "Thinking aloud may be the single most valuable usability engineering method" [14]. There is no detailed description on how to do this process in the literature and can, therefore, vary from different practitioners.

2.3.5 Interviews

Interviews are a useful way of obtaining in-depth information about user experience but take time to conduct and are challenging to analyze and compare [1]. Interviews resemble everyday conversations, although they are focused on the researcher's needs for data. They also differ from an everyday conversation as they are conducted in a way that ensures reliability and validity (i.e. 'trustworthiness'). The researchers and has to be confident that the findings reflect what the research set out to answer, rather than reflecting the pre-existing bias of the researcher. In practical terms, this means that the techniques should aim to be reproducible systematic, credible and transparent [13].

2.3.6 Focus Groups

Focus groups or workshop are a form of group interview that uses communication between research participants to generate data. Although group interviews are often used merely as a quick and convenient way to collect data from several people simultaneously, focus groups explicitly use group interaction as part of the method. Group interaction means that instead of the researcher asking each person to respond to a question by turn, people are encouraged to talk to one another: asking questions and commenting on each other's experiences and points of view. The method is useful for exploring people's knowledge and experiences. It can be used to examine not only what people think but how they think and why they think that way [15]. Focus groups are described as workshops in the next chapters of this thesis.

2.3.7 Ethical considerations

A researcher has the responsibility of the research participants and the people that will be presented in the findings. One starting point in considering ethical concerns are the four principles of Tom Beauchamp and Jim Childress (1983) [16]:

- **Autonomy** - Respect the rights of the individual
- **Beneficience** - Doing good
- **Non-maleficience** - Not doing harm
- **Justice** - Particularly equity

It is essential to consider carefully the context and aim of the research and how sensitive the topic might be. Could the questions be traumatizing or might they make the respondent(s) uncomfortable/fearful of consequences? Asking a person to talk about a experience that was frightening, humiliating or painful can cause or increase anxiety. It is, therefore, crucial to take care in how the question is asked as well as when and where. Two vital ethical issues that should be considered in any project are consent and confidentiality [16].

- **Consent**

  Participants in the research study should have freely consented to participation, without being unfairly pressurized. This means they should be well-informed about what participation implies, and ensure that declining will not affect any services they already are receiving. While written consent may in some situations frighten the individuals, a verbal consent should at least always be obtained [16].

- **Confidentiality**

  It is rarely easy or even possible to measure the consequences of a certain context to a given population or individuals. It is therefore important to protect the identity of the person from whom information is gathered. If the identity of the participants is collected, it must be protected at all times and not be left lying around in notebooks or unprotected computer files. NSD (Norwegian Center for Research Data) suggest as followed [17]:

  > *" In order for a project not to be subject to notification, all electronic data processed through the entire research process has to be anonymous. In addition, no sensitive data can be linked to directly identifiable personal data, nor via code or reference number referring to a separate list of names (scrambling key)."* (NSD, 2018)

  The following methods are gathered from the NSD website [17]:

- In carrying out interviews and/or observations, data is recorded exclusively in the form of notes (not recordings). One must ensure that no name and no personally identifiable background information is registered in the data material.
- There can be made audio recordings of interviews if the interview guide is designed in such a manner that no personal data will appear in the recordings. (NB! Voice combined with background information about the informant may in some cases be personally identifiable. When using audio recordings, this type of information has to be omitted or limited in such a way that individuals cannot be recognized in the data material.)

- Paper surveys can be carried out, as long as neither names nor any sensitive personal data is registered.
- For online surveys not to be subject to notification, one has to make sure that the IT solution is completely anonymous (among other things, the respondent's email or IP address cannot at any moment be connected to the survey), and that the survey does not contain questions about identifiable information. NB! Most online surveys do register email or IP address, and using these will make the project subject to notification, even in cases when only the data processor has access to identifiable information.
- Data from records and registries can be used without making a notification as long as only anonymous data is extracted. The information can in no way be traceable to individuals. Several anonymous registry data is available online, for instance at SSB and NSD.

2.3.8 How the literature review these methods

Choi and Sprigle (2011) conducted a project aimed to compare different methods of evaluating prototypes to determine which hold promise as aids to designing new assistive technology products. Their project concluded with the following:

> *"In conclusion, the results indicated that a short, directed usability questionnaire administered after performing a task could represent a time-effective means of evaluating usability. This could be useful during the design process to obtain a quick, simple, and reasonably accurate opinion of a device. The questionnaire did not adequately distinguish between effectiveness and satisfaction of prototypes, so the total score is the most useful metric. A single overall opinion question may also be a useful measure of prototype usability."*
> (Choi and Sprigle, 2011)

Kitzinger (1995) conducted a paper aimed to introduce group methodology and how to use focus groups. This paper concluded with the following [15]:

> *"Group data are neither more nor less authentic than data collected by other methods, but focus groups can be the most appropriate method for researching particular types of question. Direct observation may be more appropriate for studies of social roles and formal organizations, but focus groups are particularly suited to the study of attitudes and experiences. Interviews may be more appropriate for tapping into individual biographies, but focus groups are more suitable for examining how knowledge, and more importantly, ideas, develop and operate within a given cultural context. Questionnaires are more appropriate for obtaining quantitative information and explaining how many people hold a certain (pre-defined) opinion; focus groups are better for exploring exactly how those opinions are constructed. Thus while surveys repeatedly identify gaps between health knowledge and health behavior, only qualitative methods, such as focus groups, can fill these gaps and explain why these occur."* (Kitzinger, 1995)

2.4 Prototyping

This section presents theory acquired about prototyping during this masters' project. It explains what prototyping is, what they can be used for, and their purpose.

2.4.1 What is prototyping?

Prototypes are a commonly used tool when working with product development. A prototype is made to gather information about some unknown elements of the product. Ulrich and Eppinger define prototypes as "an approximation of the product along one or more dimensions of interest" [12]. Prototyping, on the other hand, can be viewed as the process of creating a prototype [12].

Ulrich and Eppinger argue that prototypes can be classified along two dimensions. The first dimension is whether the prototype is physical or analytical. A physical prototype is built as an approximation to the finished product. It can be used as a proof-of-concept and to quickly test ideas as well as produce the look and feel of the finished product. Analytical prototypes, on the other hand, are usually mathematical or visual. Such prototypes can be used to visualize and analyze a product and are generally cheaper than physical prototypes. Examples of such prototypes are computer finite element analysis and 3D-models [12].

The second dimension focuses on whether the prototype is comprehensive or focused. Comprehensive prototypes contain most of the characteristics of the finished product. These prototypes are what most people are thinking of when they hear the word prototype. Focused prototypes, however, consider only a few of the characteristics of the product. As an example, clay can be used to show the shape of the finished product. This type of model is focused, as the shape is one of the few insights it provides. Several focused prototypes can be combined, creating a greater understanding of the product [12].

How the dimensions correspond to different kinds of prototypes can be seen in figure 2.4.

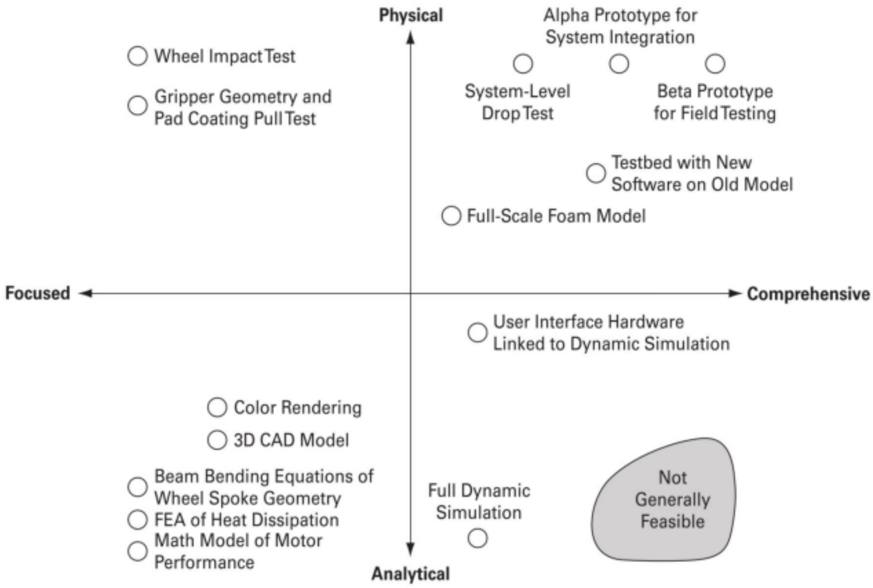


Figure 2.4: Prototypes according to their respective dimensions [12]

2.4.2 Purpose of prototyping in new product development

According to Ulrich and Eppinger (2011), prototypes are used for four purposes [12]:

Learning

Prototypes are generally used to answer two types of questions: ”Will it work?” and ”How well does it meet the customer needs?”. In this regard, prototypes are used as learning tools [12].

Communication

Prototypes are very useful for communication with top management, vendors, partners, team members, investors, and customers. This is especially true when it comes to physical prototypes. A visual and three-dimensional representation of a product is much easier to understand than a verbal description or a sketch [12].

Integration

Prototypes are also used to make sure that subsystems and components of a product will work together as intended. For integration, comprehensive physical prototypes are most effective and suitable. With these type of prototypes, it is possible to assemble parts and detect potential problems [12].

Milestones

Prototypes can be used to demonstrate that the product has achieved a desired level of functionality. This is more common in the later stages of the product development. These milestones can be necessary to show management, investors or customers that the project is going according to plan [12].

2.4.3 Planning the prototype

Prototyping can be a complex work method which requires extensive planning. All prototyping has a cost, either the price of used materials or the hourly pay of the engineer making a simulation. Without proper planning, there is a risk of ending up with a costly prototype that does not create the value required for the project. Ulrich and Eppinger present a four-step way of planning prototypes to eliminate this threat [12].

- **Step 1: Define the purpose of the prototype**

  Prototypes have mainly four purposes; learning, communication, integration, and milestones [12]. The first step of the prototype planning is to decide specific learning and communication needs. This is followed by recognizing any integration needs and whether or not the prototype is going to be one of the milestones in the project [12]. One or more of these purposes can be chosen as the prototypes purpose. This ensures that the cost of the prototypes brings the project further in some way.

- **Step 2: Establish the level of approximation of the prototype**

  This step involves deciding to which degree the prototype is going to be an approximation of the finished product. As an example, a choice that should be decided early is whether the prototype is going to be analytical or physical. As a general rule, analytical prototypes are cheaper, but physical prototypes may produce result unavailable by analytical methods. Generally, it is beneficial to make the prototype as simple as possible while still serving the purpose decided in step 1 [12].

- **Step 3: Outline an experimental plan**

  A prototype can in many ways be viewed as performing an experiment. Regular experimental methods should, therefore, be performed to ensure the maximum retrieval value from the prototype. Such experimental plan should contain the measured variables, a test protocol, measurements that will be performed and a plan for resulting data-analyzing.

- **Step 4: Create a schedule for procurement, construction, and testing**

  The prototype process can be seen as a project of its own. The process is initiated to produce results used further in the general product development process. To get the result within an expected time frame, it is important also to plan the prototyping process. There are especially three important events to plan; Finished prototype, First test and Final results.

2.4.4 Early vs late stage prototypes

Prototypes are used for different purposes in the design process. In general, these stages can be divided into early and late stage prototypes. The early-stage prototypes are made to express an idea without using a lot of time and effort. They can help to spark the imagination and can be used as a conversation piece. Early stage prototypes can also reveal problems and bring questions to the solution or design [18]. The late-stage prototypes are used to validate design and solutions. They are closer to the final product and are more defined and detailed compared to early-stage prototypes. One aspect of testing with late-stage prototypes can be manufacturability or test different component assemblies.

2.4.5 ”Cobbled up” prototypes

”Cobbled up” prototypes is a method introduced to the authors by one of the professors in a class at NTNU (Christer Elverum, Advanced Product Development). By ‘cobbled’ up Elverum mean prototypes that are mainly built from off-the-shelf parts. With extensive use of such parts, it is possible to test concepts quickly with low costs and at the same time create highly functional prototypes [19].

2.5 Prototyping methods

The following section presents the different prototyping methodologies used during this masters’ project.

2.5.1 Rapid prototyping

Rapid prototyping takes advantage of the drastic price drop in prototype production that has occurred the recent years. The 3D-printer is a great example of a prototyping-tool that has reduced costs significantly. Rapid prototyping takes advantage of this price drop, not by saving money, but by making more prototypes faster. The method of prototyping highly increases the speed of information collection. It removes the lead time from the equation. The price reduction also makes it possible to start producing cheap prototypes earlier in the process [19]. Additive manufacturing methods are in general used in rapid prototyping. Typical methods can be stereo-lithography apparatus (SLA), selective laser sintering (SLS), Fused deposition modeling (FDM), Laminated object manufacturing (LOM) and Ballistic particle manufacturing (BPM) [20]. Based on recent development and price, FDM is popularly used for low budget prototyping.

2.5.2 Set-based prototyping

A problem with many prototypes is the limited knowledge that can be retrieved from them. So-called point-based prototypes are made to answer a simple question; will it work or not. Even though the answer to this question is “yes” or “no” it gives little insight in what could be improved further, or as Elverum (2017) describes it “lack of knowledge on optimization” [19]. A way of dealing with this problem is to use the set-based mentality when prototyping. Instead of making a single prototype, plenty of prototypes should be made simultaneously to achieve multiple data points and increase the knowledge gathered from the prototyping process. These points of data can be collected and compared in a highly scientific manner. However, this kind of prototyping can become resource demanding. Both building and testing larger numbers of prototypes steal resources from other necessary parts of a project. Another problem is that the variables being tested by the prototype might be too complex. As an example, set-based prototyping works great when testing the impact capability of a bicycle wheel. However, if the test considers the more complex "feeling" of riding the bicycle, it becomes much harder to achieve valuable results.

2.5.3 Set-based prototypes

As a solution to the problem with set-based prototyping, Elverum (2017) suggests a new term called set-based prototypes. Set-based prototypes can be described as flexible prototypes were the variables can be changed during testing. This kind of prototype may increase the amount of knowledge gathered from each prototype [19]. Set-based prototypes work well for uncertain early phases where it is necessary to explore multiple concepts. Elverum (2017) states that this is considerably less scientific than set-based prototyping. Set-based prototypes are considered useful when looking at the overall system and not just specific parts. It is a top-down rather than a bottom-up approach, meaning it starts with an entire concept instead of building knowledge on parts of the concept. The purpose of the prototype is to hedge your bets rather than conducting step-by-step science to build a substantial knowledge base that results in limited curves [19].

2.6 Start-up companies and prototypes

Some innovation cultures are specification-driven while others are prototype-driven. Start-up companies built around a brilliant product concept tend to be prototype-driven. Companies that need to coordinate large volumes of information, tend to be specification-driven. Specification-driven cultures also draw heavily from market research data before concepts are moved into the prototyping cycle. In prototyping cultures, prototypes are often used to obtain market feedback before final production [21].

Prototypes may reduce the risk of costly iterations, which could be especially important for a start-up company [12]. By taking time to build and test prototypes, the development team can find problems that would otherwise not have been detected until after a costly development activity, such as doing an extrusion or building an injection mold. Making changes early in the design process are considered cheaper than making changes later [19]. On the other hand, the benefits of reducing risk must be weighed against the time and money required to build and test the prototypes [12]. Products or parts that are in high risk of uncertainty, high costs of failure or new technology are considered to be beneficial of such prototypes [12].

Chapter 3

Method: Prototyping

The following chapter presents the prototyping performed during this masters' project. The process follows the planning procedure presented by Ulrich and Eppinger (see Section 2.4.3). Each prototype presentation also begins with a description of the problem it is trying to solve. The presentation is meant to give the reader an overview of the overall purpose of the prototype, as the development process is not covered in this thesis (see Section 1.8). The testing of each prototype is presented in a later chapter and in the appendix (see Chapter 4 and Appendix B).

Each prototype process contain the following:

- Description of the problem
- Purpose of the prototype
- Level of approximation
- Experimental plan
- Schedule procedure for construction and testing

3.1 Set-based prototypes

This section describes the different processes that were conducted to create set-based prototypes during this masters' project.

3.1.1 Width-adjustable seat prototype 1

Planning the prototype

One of the more difficult tasks with Spike and Spear was considered to be the seating. The challenge was in most part to give the user enough support and comfort while still being fastly secured in the seat. To give enough support, a seating with supporting side-walls had shown to be beneficial. Side-walls, however, creates a problem as the size of individuals buttocks can vary by a significant amount. Some disabilities lead to weight gain as exercising becomes difficult, while others lead to weight loss in areas were muscle mass fades away. The individual sizes, combined with the need for supporting side-walls close to the body for optimal support, lead the team to believe that different seat sizes were necessary. This resulted in the need to uncover the size variety of buttockses in the user-group. It would also be essential to discover the number of different seating sizes necessary to serve the user group.

The prototype had the following purpose:

- Discover the buttocks variations within the user-group
- Discover the number of different seat sizes necessary
  (How large/small is too large/small)

To be able to fulfill the second purpose of the prototype it was seen as necessary to create a focused prototype (see section 2.4.1). Maneuvering by leaning to the sides makes contact between the user and the seating, a crucial part of the design. With a large seat, the user might slide within the seat instead of pushing/steering the sled. This aspect would be the only parts of the product the prototype would be focusing on.

It was also decided to go straight for a physical prototype. It was argued that a fast and easy ”cobbled up” prototype would be sufficient for the purposes. The benefit of a ”cobbled up” prototype was the ability to create a physical prototype early while still keeping a low cost (see Section 2.4.5). The idea was to make a width adjustable seat and retrieve user feedback with Spike at different widths.

Experimental plan:

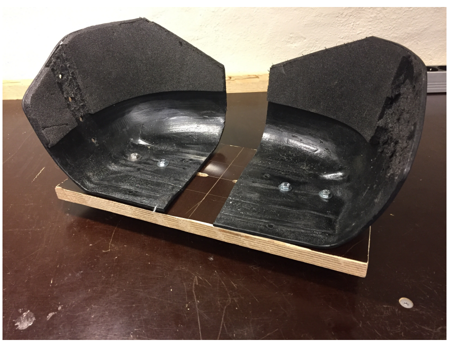
1. Research available materials
2. Discuss simple mechanical solutions based on available materials
3. Build a cobbled up prototype
4. Test the prototype in-house and with users

The prototyping process was planned to begin on November 3 with focus on uncovering available materials and developing a mechanical solution. The building process would focus on speed and creation of the simplest and cheapest prototype possible. This building process was planned to begin on November 6 and be finished the day after at November 7. The testing was scheduled to begin two days after, on November 9. A two day waiting period was put in, taking possible delays into account.

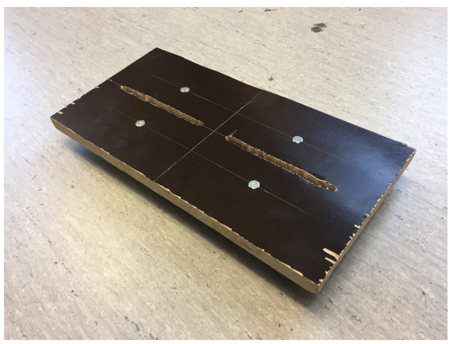
Execution of the prototyping process

The process began as scheduled at November 3. From reviewing available materials, it was decided to re-use an existing seat prototype (see Figure 3.1). The seat was a rigid plastic shell which was cut in half on the middle (see Figure 3.2a). The cutting was performed to make the sidewalls independent of each other. The width adjustment mechanism was decided to be made by wooden materials. This was decided due to its availability, and cost of both materials and woodworking tools. The prototype was designed to make the two seat-walls slide along two tracks milled into a wooden board (see Figure 3.2b). The width was secured by two M4 bolts going through both the tracks in the wooden board and holes in both seat parts. When tightened, the friction between the parts, provided by tightened bolts and nuts, prevented the parts from sliding further along the tracks. On the back side of the board, existing milled aluminum brackets were mounted, to enable the prototype to be mounted to the existing Spike prototype.

Figure 3.1: Original plastic seat shell



(a) The finished prototype 1 with no padding



(b) The wooden base plate with adjustment-tracks

Figure 3.2: Width adjustment prototype 1

3.1.2 Width-adjustable seat prototype 2

Planning the prototype

Results from seat prototype 1 showed a clear advantage with the width-adjustment (see Section 5.1.1). It was therefore decided to incorporate the set-based solution into the actual product. To be able to do this, it would be necessary to explore how the mechanical solution could be developed into the product. The decision would affect both the design of the sled in general and especially the shape of the seat. It was decided that 3 mm sheet metal and 20 mm aluminum tubing should be used in the design if possible. This was decided as beneficial for manufacturing as these elements already were being used in other areas of the product.

As the set-based solution was integrated as a feature, it would technically no longer be viewed as a set-based prototype. However, to ease the reading process, all the seat prototypes will be presented in the following s in chronological order.

The prototype had the following purpose:

- Discover a solution for implementing width-adjustment into the seating
- Discover a possible seat design that fits the visual characteristics of Spike
- Get a strength estimate of the chosen solution

For this prototype, an analytical prototype had its distinct advantages (see Section 2.4.1). An analytical prototype would keep flexibility and enable ”trial and error” during the implementation of the width-adjustment. A CAD-model would also be flexible as a FEM-analysis could be used for strength estimating. A physical prototype would be much more dependant on destructive testing which would lead to higher total costs. Deciding on creating a 3D CAD model meant that the prototype would be ”focused” (see Section 2.4.1). It would focus on visual design, mechanical functionality, and strength, all inside the analytical design space. This would limit the feedback available from users but was seen as a ”necessary evil” compared to the flexibility that would be achieved. The prototype would aim towards the visual and mechanical design of the finished product.

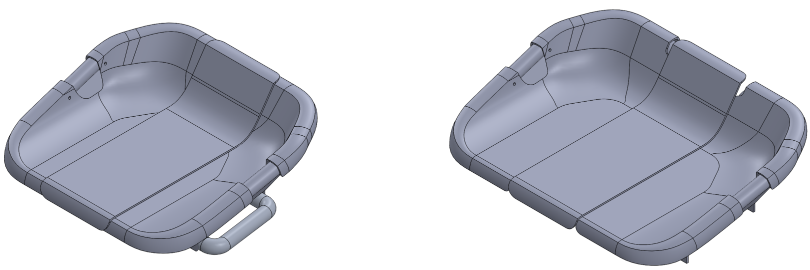
Experimental plan:

1. Sketch out different seating designs
2. Create an ergonomic seating shape with the implementation of an aesthetic design
3. Design and decide on a possible width-adjustment mechanism
4. Perform FEM analysis on the prototype to indicate its strength limits

Based on the results from seat prototype 1, a new prototype process was planned to start early in the masters' project (see Section 5.1.1). The process was scheduled to begin at February 5 and would first consider the research of different mechanical solutions to use for the width-adjustment. The research and sketching of different possible designs were planned to last for two days. The modeling process would then take three additional days. It would focus on both creating an ergonomic design while implementing the adjustment solution. The modeling was scheduled to be finished at February 8, with a FEM analysis following soon after. The whole process would be finished at February 9.

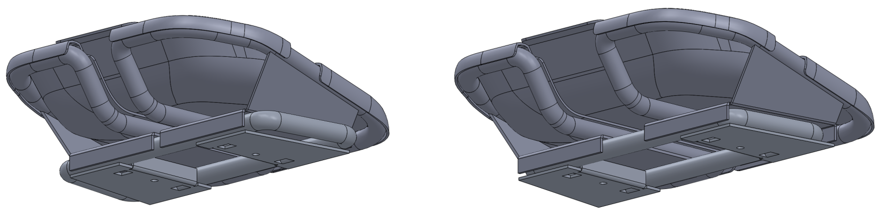
Execution of the prototyping process

The process began as scheduled at February 5. During researching and sketching, it was soon realized that it was difficult to evaluate all the solutions. Several solutions were therefore taken further and modeled in 3D. Several hopeful ideas turned out to be flawed soon after the modeling process began, which led to a quick rejection of solutions. Some, however, took longer before rejection which led to a delayed process. The complexity of the 3D modeling also leads to a time-consuming process. Due to reasons mentioned above, the final prototype was not finished before February 23. It consisted of three main parts, one center-part and two sidewall-parts which were able to slide on a frame creating the width-adjustment mechanism (see Figure 3.3 and Figure 3.4). When in position, the sidewalls would be kept in place by friction between the tube frame and two sheet metal parts. The tubing was also added to the seat walls to increase its strength. Exero had observed that users with limited function in their legs tended to grab the sidewalls to support their full body weight when mounting the sled. The solution was similar to the original concept of prototype 1. After finishing the modeling process, the strength of the seat was calculated using FEM-analysis in SolidWorks simulations. At this stage in the development process, it was only performed a simple static analysis to get rough estimates of the strength. This was done to save time in case the prototype had to be scrapped later in the process.



(a) Seat at minimum 310 mm width **(b)** Seat at maximum 420 mm width

Figure 3.3: Seat seen from the front at minimum and maximum width



(a) Seat at minimum 310 mm width **(b)** Seat at maximum 420 mm width

Figure 3.4: Seat seen from the rear at minimum and maximum width

3.1.3 Width adjustable seat prototype 3

Planning the prototype

Before deciding on the final concept, it was seen as necessary to test the design further. As the Exero team had no previous experience creating ergonomic seating, it would be beneficial to learn more about the chosen design, before investing money in manufacturing tooling.

The purpose of the prototype was the following:

- Learn about the design chosen during creation of the analytical seat prototype 2 with focus on ergonomics

To be able to get feedback on the users' experience, it was essential to create a physical prototype. While an analytical prototype could give some insight into what users believed the seat would feel like, only a physical prototype would be able to give a distinct answer (see Section 2.4.1). The prototype would be "focused", considering the ergonomic shape of the seating alone. To fulfill the purpose, it would still be necessary with some width adjustment mechanism, to mimic the feeling of the actual seat. While the seat shape itself would need to resemble the final product to fulfill its purpose, it would be made no such effort on the mechanical adjustment system.

Experimental plan:

1. 3D-print the seat shaping of the analytical seat prototype 2
2. Mount the seating shell to the mechanical adjustment prototype used in seat prototype 1
3. Test the seating ergonomics in-house
4. Mount the seating to the Spike prototype
5. Perform in-house and user testing while riding the Spike prototype

The 3D-printing was scheduled to begin on February 26 shortly after results from the analytical prototype were reviewed. The 3D-printing itself was calculated to take 19 hours. As the adjustment mechanism already was created, the assembly process would be performed the following day on February 27. It would then be tested in-house (see Section 4.2) by the members of Exero and then by users. The in-house testing would occur as soon as the prototype was finished on February 28. The user testing was scheduled to be performed during March giving enough time to redesign and re-print the shells if problems would occur during in-house testing.

Execution of the prototyping process

The building of the prototype went according to schedule. The 3D-printed seating assembled to the wooden adjustment plate (see Figure 3.2b) with no complications (see Figure 3.5).

Figure 3.5: The finished prototype 3 with no padding

3.1.4 Width adjustable seat prototype 4

Planning the prototype

At last, it was decided to 3D-print a whole seat as a milestone prototype (see Section 2.4.2). This would help the team to see the final design as well as uncover potential flaws. To reduce 3D-print materials, it was decided to first print a smaller version in 1:5 scale of the original size. Potential flaws would then be corrected before a full-scale print would be initiated. Pillows would later be sewed on to the future manufactured seat shells. The sewing company had previously stated that it would benefit their planning, having a physical prototype available.

The purpose of the prototype was the following:

- Learn about flaws in the final design
- Communicate with stakeholders, manufactures, etc.
- Update the whole Exero team on the progress

The seat did not need to be fully functional, however, it was important that it could show the width adjustment mechanism and the correct geometry. The prototype would be physical and ”focused” (see Section 2.4.1). It would be used to learn about potential flaws and to communicated with vendors (see Section 2.4.2).

Experimental plan:

1. 3D-print the seat based on prototype 3 in 1:5 scale
2. Inspect and measure the 1:5 size model
3. Correct eventual flaws
4. Repeat print in 1:1 scale
5. Assemble and control functionality
6. Present the prototype to the entire Exero Technologies team

The 3D-printing was scheduled to begin on April 26 based on results from prototype 3. The 3D-printing itself was calculated to take 3 hours for the small version (1:5). The adjustment mechanism would also be 3D-printed and needed to be inspected when the first version was ready. The assembly process would be performed the same day. It would then be tested in-house by the members of Exero. Based on the findings, a new version in 1:1 model would be made the next day. This print was estimated to take about 48 hours to finish. Then a new test would be done in-house to check if the adjustment mechanism works as intended.

Execution of the prototyping process

The building of the prototype went according to schedule. The 3D-printed seat in 1:5 scale worked as intended (see Figure 3.7a and Figure 3.7b).

As the 1:5 scale worked as intended a 1:1 scale model was built. Due to the large size, each part could not be printed as a whole. They were therefore split and printed in several stages. Afterward, they were glued together. After two days the model was finished and worked as planned (see Figure 3.6 and Figure 3.7).

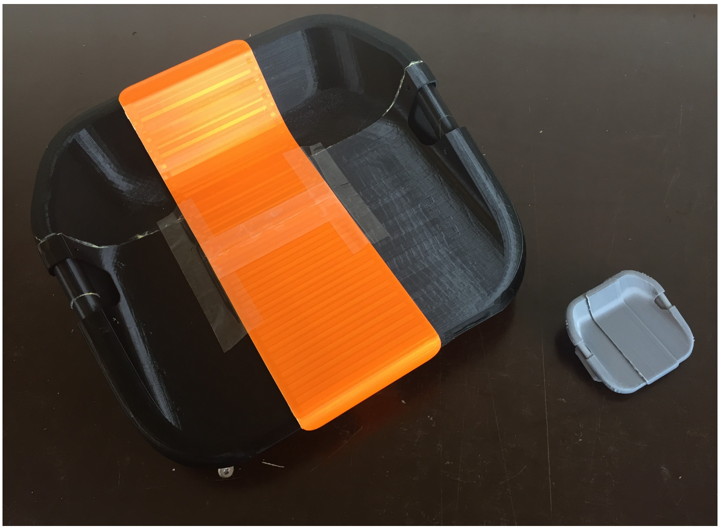
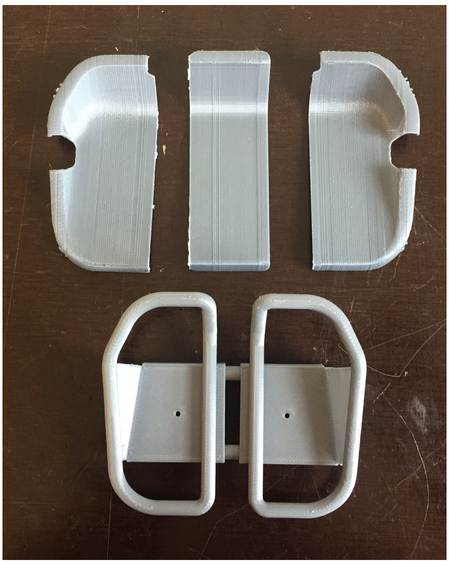
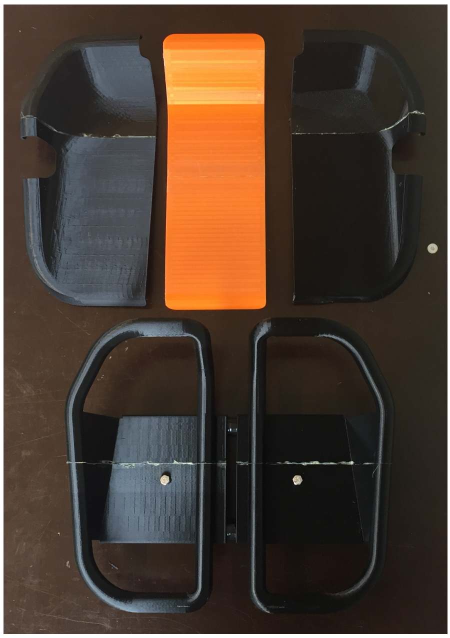


Figure 3.6: A comparison of the 3D-printed seats



(a) Disassembled 3D-printed seat in 1:5 scale



(b) Disassembled 3D-printed seat in 1:1 scale

Figure 3.7: Disassembled 3D-printed seats

3.1.5 Truck Angle Adjustment Prototype

Planning the prototype

The truck-angle of the steering system has a great effect on the responsiveness of the steering system (see Figure 3.8). This responsiveness had both a positive and negative effect on the steering for both Spike and Spear. With a large angle, the steering-system becomes more responsive which leads to a smaller turn radius. This effect is beneficial for the user. However, it also leads to the steering system responding increasingly to the users' movement. Previous testing had shown that it was difficult to keep the body correctly centered on the sled when going straight. An over-responsive steering system would, therefore, make the user turn more often than intended which leads to continuous correcting. To learn about the middle-ground between a responsive system and over-correction, different angles would need to be tested on users and a decision made based on the response.

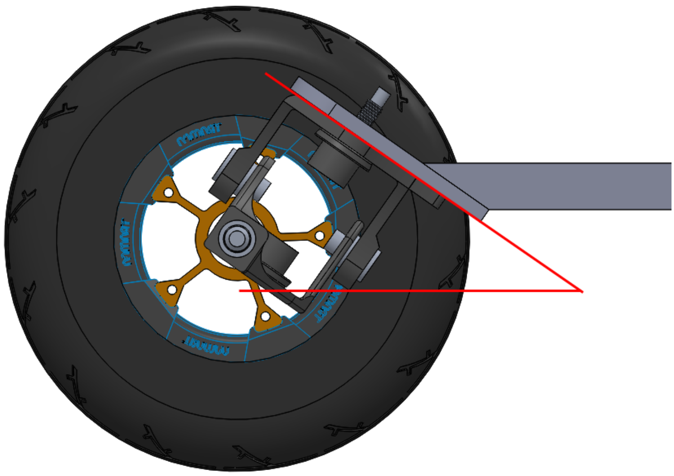


Figure 3.8: The truck-angle of the steering system

The angle adjustment prototype had the following purpose:

- Learn about the truck angle's effect on the steering and the users experience
- Decide an optimal truck angle

The prototyping was planned to be executed in two stages with one analytical and one physical prototype (see Section 2.4.1). First, a brainstorming session would be performed to decide on a possible solution for angle adjustment. It was early decided to create a set-based prototype with the ability to change the angle on the steering system easily. To ensure that the solution would work mechanically, it would first be created a 3D-model as an analytical prototype. This would give the flexibility to make changes during development at low costs. The second prototype would be physical and built as a copy of the analytical one. This prototype would be used to perform the actual user-testing. Both prototypes would be ”focused”, only considering the turning-capability of the sled, and not be an approximation of the finished product. It was decided that Spike and Spear would have a fixed angle to prevent weakness and looseness in the frame. The benefit in approximating the finished product was therefore minimal.

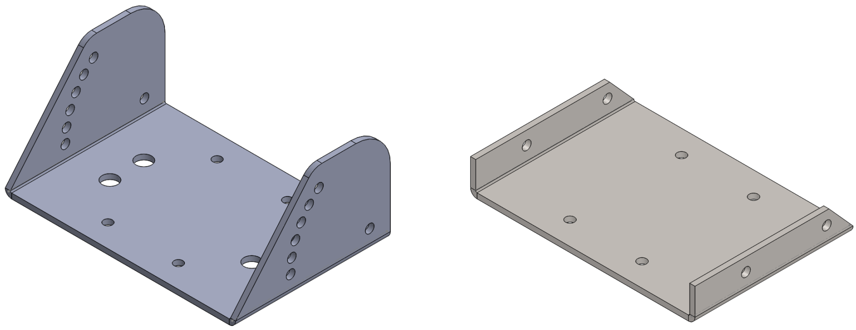
Experimental plan:

1. Brainstorm and evaluate different solutions
2. Pick a solution and create an analytical prototype (CAD)
3. Check if the solution works mechanically within the analytical boundaries
4. Remake or correct the analytical prototype if needed
5. Create a physical prototype based on the analytical model
6. Test the physical prototype in-house for turn radius measurements
7. Test the physical prototype with actual users to correlate turn radius with user experience

The brainstorming was scheduled to begin at January 20. A single day of brainstorming was planned before the development of the analytical prototype were to begin at January 21. The modeling was planned to take two days and finish on January 23. When satisfied, the drawings would be generated from the model and delivered to Ula Jern (a mechanical workshop used during the pre-masters project, see appendix A). The manufacturing was expected to take approximately one week with delivery on January 30. The testing of turn radius was planned to be performed in-house on February 2, while the experience testing with a user was planned to occur a week after at February 9.

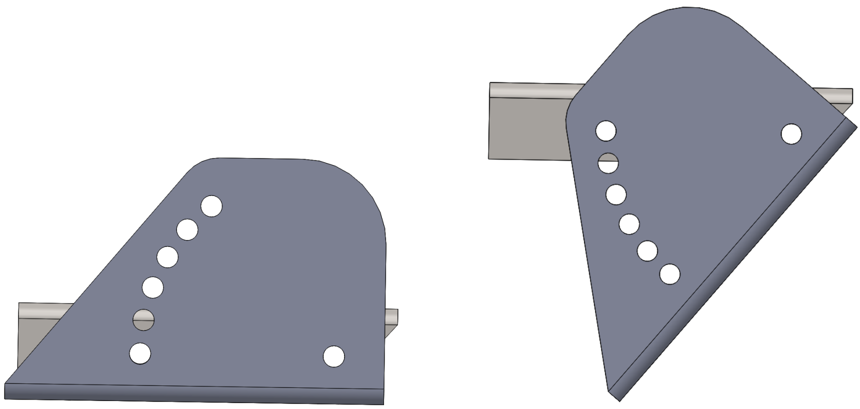
Execution of the prototyping process

The brainstorming session began as planned on January 20. The angle-adjustment mechanism had been discussed in Exero previous to this project, so some ideas were already thought out. The team focused on creating a solution that would be easy to handle and cost-effective. On January 21, the 3D-modelling began. The solution consisted of two main parts. Both would be manufactured by cutting a steel plate and bending two sides upwards 90°. Steel was chosen as it would create an over-dimensioned part which led to the assumption that simple strength calculations would suffice. The extra weight gained by choosing steel was not seen as influencing the performance of the prototype. Part A (see Figure 3.9a) would be bolted to the sled frame, while part B (see Figure 3.9b) would be bolted to the truck. The side-walls of part B were designed with seven holes, one ”center-hole” and six ”adjustment-holes” in an arc 46 mm from the center-hole rising in steps of 10°(see Figure 3.10). Four bolts also connected part A, and part B. All bolts would be fastened with lock-nuts except the bolts going through the ”adjustment holes”. Here the bolts would fastened by regular nuts to ease the fastening and loosening of the bolt when performing adjustments. A 45°chamfer where also cut on part B to prevent contact between the parts (see Figures 3.9b and 3.10b).



(a) Part A **(b)** Part B

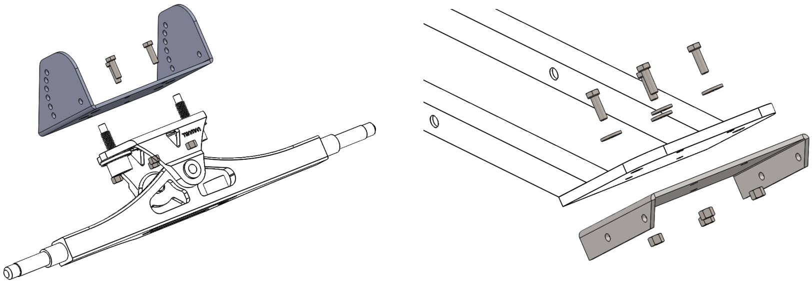
Figure 3.9: Figure showing the two main parts of the prototype



(a) The prototype at minimum angle **(b)** The prototype at maximum angle

Figure 3.10: Figure showing the tilting mechanism of the prototype

On January 23, the CAD-model was checked for mechanical collisions with both the sled-frame and the truck-system. The check was performed visually and by using the SolidWorks-function ”Detect Collision” at different angles. All the holes were also checked for alignment at all the adjustment angles. When the CAD model worked mechanically as intended, the assembly procedure was reviewed to ensure easy mounting and assembly. Each part was assembled in the CAD environment in the same way and order as it would be on the physical prototype. Part A and part B were first connected to the frame and the steering-truck (see Figure 3.11). The order of assembly was chosen to obtain maximum clearance for tools to simplify the assembly process. For the last step to be feasible, it was crucial to leave enough space between the parts to fit a wrench. The width of the wrench was measured to 13 mm and the distance between the to parts where therefore put to 17 mm. This was also important as the bolt in the adjustment-holes would be assembled and disassembled every time the angle would be changed. On January 24 the mechanical drawings were generated and sent to Ula Jern.



(a) Prototype assembly step 1 **(b)** Prototype assembly step 2

Figure 3.11: Figure showing the tilting mechanism of the prototype

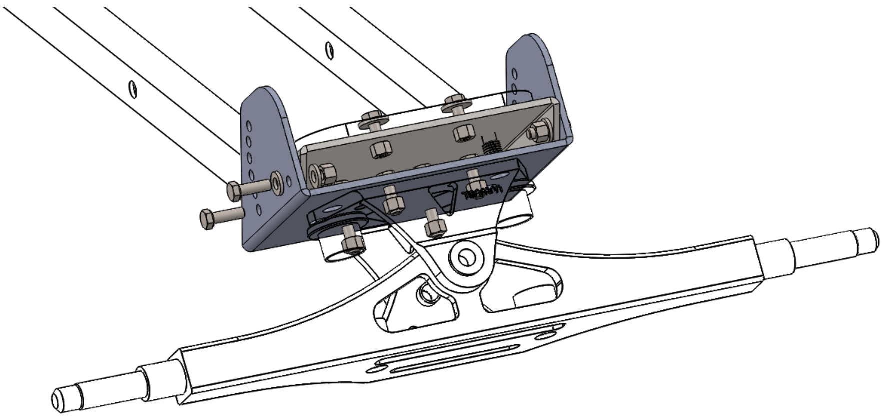
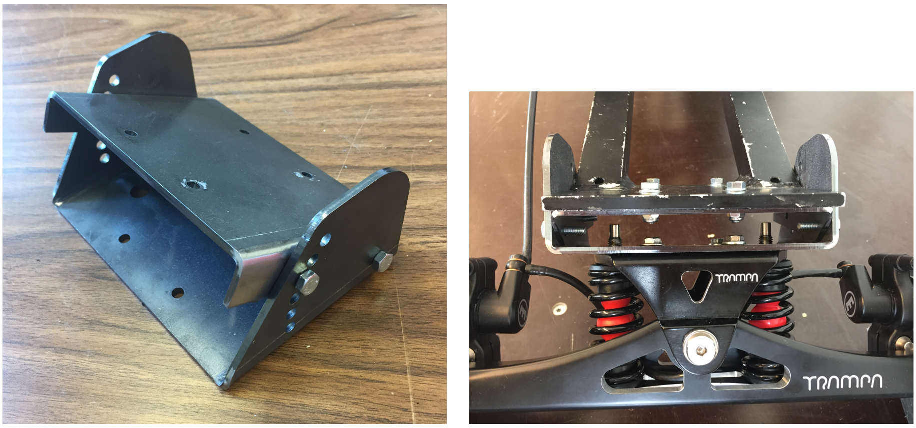


Figure 3.12: Prototype assembly step 3

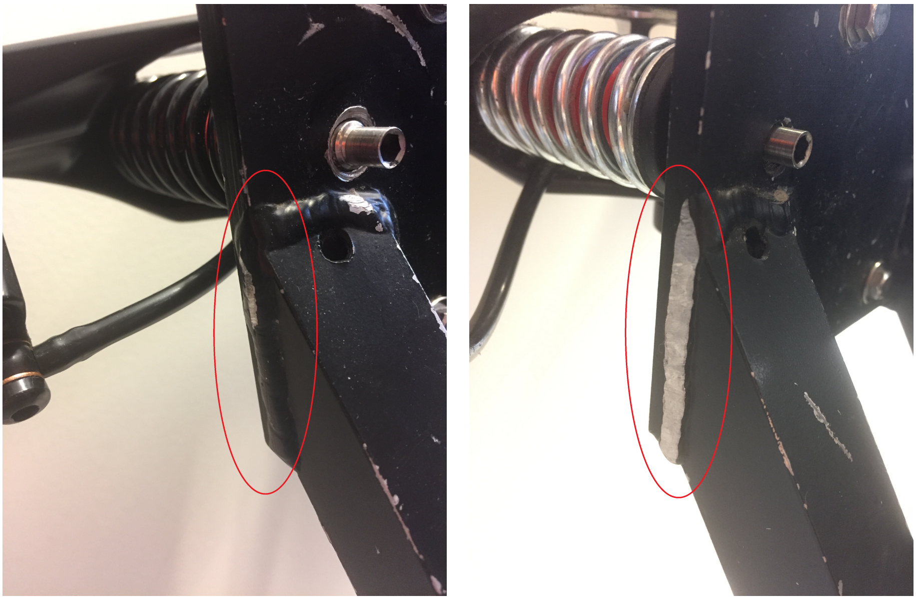
Two sets of the angle adjustment prototype were ordered to be mounted both in the front and rear of the Spike prototype. The workshop responsible for creating the prototype was lacking sufficient experience with sheet metal bending and out-sourced the job to a third-party company. This created some miscommunication regarding necessary drawing and data files. This, in addition to low response time from both companies, led to a delay of 17 days. When the parts finally arrived however, they were according to specification. The parts were first mounted together to check if they behaved as intended by the analytical prototype (see Figure 3.13a). It was then attempted to fasten the prototype to the Spike prototype in the same sequence as shown on the analytical prototype. During assembly, it was discovered that the truck mounting plates of the Spike prototype (see Figure 3.11b) was 3 mm wider compared to the analytical prototype. The extra width prevented the mounting plate from fitting between the walls of part A (see Figure 3.12). The extra width originated from a weld seam created during manufacturing of the Spike prototype. These were not correctly included in the analytical prototype. To solve the problem, the weld seams were ground down on both sides of the sled (see Figure 3.14a and Figure 3.14b). Afterward, the assembly worked as designed (see Figure 3.13b). Testing was then performed with the prototype both in-house and with users. The turn radius was tested in-house with the same procedure as later explained in the test chapter (see Section 4.2.2).



(a) Angle prototype assembled alone

(b) Angle prototype assembled on Spike

Figure 3.13: Physical prototype assembled on the existing Spike prototype



(a) Original weld seam of Spike prototype **(b)** Weld seam of Spike prototype after grinding

Figure 3.14: Weld seam on Spike prototype

3.1.6 Wheel count and wheelbase prototypes

Planning the prototype

Another influential factor to the steering is the relative positioning of the wheels. As the truck-system is mostly used on skateboards and other recreational equipment, they share somewhat the same relative wheel positioning. It was, therefore, difficult to find research on how other wheel positions would affect the steering. To get an overview of the effect of each parameter, it was decided to test it through prototyping. The parameters that were viewed as interesting were the following:

- The wheelbase (distance between the two axles)
- Wheel count (number of wheels on the sleds)

Especially interesting were the parameters effect on turning radius and stability. The prototype would have a focus on learning (see Section 2.4.2).

The prototypes had the following purpose:

- Learn the effect of wheelbase on steering radius and stability
- Learn the effect of wheel count on steering radius and stability
- Decide on the optimal combination of the parameters mentioned above

For the prototype to be able to fulfill its purpose, variable parameters would be necessary. It was decided to use the Spike prototype and add smaller prototypes to it and through testing decide on an optimal combination. The prototype would only be used for short-term testing which allowed for low quality cobbled up prototypes (see Section 2.4.5). It was therefore decided to create prototype-driven physical prototypes (see Section 2.6). There would be no attempt to make the prototype resemble the final product. The prototype would instead work as experiments to learn about the effects of each parameter.

Experimental plan:

1. Research available materials
2. Research available stock items to base the prototypes on
3. Assemble a functional prototype from materials and stock items

The prototyping process was planned to begin on February 5 with focus on uncover available materials and come up with a mechanical solution. The building process would focus on speed and creation of the simplest and cheapest prototype possible. This building process was planned to begin on February 12 and be finished the day after at February 13. The testing was scheduled to begin two days after, on February 15.

Execution of the prototyping process

It was quickly realized that several prototypes were necessary to test the different parameters. For the wheelbase parameter, it would have to be tested both with the wheel count of three and four wheels. The first prototype was simple and consisted of a standard wheelbarrow wheel mounted to the Spike prototype (see Figure 3.15a and Figure 3.16b). This wheel was mounted to the rear truck mounting plate and functioned as a first glance at a three-wheeled design (see Figure 3.16a). The aluminum wheel mount was massive in size and was, therefore, preventing it from being mounted at any position other than the truck mounting plate. It was therefore created a new mounting system by re-using the axle and ball bearings but fastening them to two wooden blocks instead (see Figure 3.15b). The wooden blocks were small enough to be mounted underneath the main frame of the Spike prototype (see Figure 3.16b). Bolts were then fastened through holes in the wooden blocks and holes in the Spike frame. Several holes in the frame created the ability to fasten the wheel at different distances from the front truck, creating different wheelbases. Only the rear wheels were moved as only these would have enough space between the feet/legs of the user. The same principle would demand a more complex solution if the front wheels were to have the same ability.

(a) Wheel bought at Biltema [22]

(b) Modified wheel from Biltema

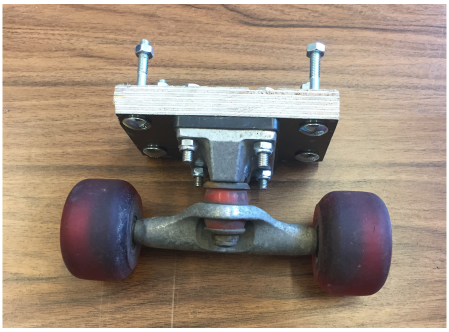
Figure 3.15: Single wheel prototypes

(a) Cobbled up wheelbarrow wheel mounted to Spike

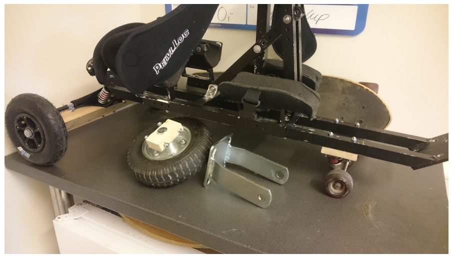
(b) Adjustable single wheel prototype mounted to Spike

Figure 3.16: Three-wheeled prototypes

To compare the wheelbase of three and four wheels, it was necessary to also create an adjustable truck with two wheels. This solution would also have to go either underneath the frame of the Spike prototype or between the legs of the user. The channel trucks already used on the Spike prototype were too large to stay clear of the users' legs in any other position than the original one. It was therefore decided to use a regular skateboard truck instead (see Figure 3.17a). These type of trucks usually has a shorter axle length and smaller wheels. These dimensions resulted in its ability to being placed underneath the frame (see Figure 3.17b). The skateboard truck was fastened to a wooden block which also would be mounted through holes in the mainframe giving it the same adjustability as the single wheel prototype.



(a) Skateboard truck mounted to wooden block



(b) Collection of different prototypes

Figure 3.17: Different wheel count and wheelbase prototypes

3.2 Set-based prototyping

This section describes the set-based prototyping processes conducted during this masters' project

3.2.1 Axle length prototypes

Planning the prototype

In addition to angle adjustment, wheel count and wheelbase, the final unknown parameter was the effects of the axle length. Axle length refers to the distance between two wheels on the same axle. After researching the mechanism of the truck system (see Section 2.1), a hypothesis was created. According to the research, the axle width would, in theory, not affect the steering radius. It would, however, have a significant effect on the stability of the product. To validate the hypothesis different axle length would need to be tested.

The prototype had the following purpose:

- Learn the effect of different axle length on the steering radius
- Learn the effect of different axle length on the stability of the sled

- Answer the presented hypothesis

The prototype would be created similarly as the wheel count and wheelbase prototypes (see 3.1.6). It would either be created as an entirely new wooden truck or by modifying the existing channel truck. As the prototype would only be used for a short duration and in low speeds, it was decided to use wooden materials on this prototype as well. It was decided to begin the process with a physical prototype. Even though an analytical prototype could provide insight into how the prototype best could be designed, it would be difficult to know what kind of geometry that would be possible to create with the tools at hand. Investing time in creating an analytical prototype could, therefore, result in wasted resources. Instead, the building began with only few preparations like short discussions and sketches within the team.

Experimental plan:

1. Research available wooden material
2. Brainstorm possible concepts
3. Choose and create a solution
4. Test the solution in-house

This prototype was built simultaneously as the ”Wheel count and wheelbase prototypes” (see Section 3.1.6). The prototyping process was planned to begin on February 5 with focus on uncover available materials and come up with a mechanical solution. The building process would focus on speed and creation of the simplest and cheapest prototype possible. This building process was planned to begin on February 12 and be finished the day after at February 13. The testing was scheduled to begin two days after, on February 15.

Execution of the prototyping process

Soon after the building process began, it became clear that creating a new truck would mean a complicated build. The complexity of the build was weighted against modifying the existing truck which seemed to be a more straightforward process. As a result, the team decided to modify the truck by adding material to it. After some trial and error, a solution was created. The solution consisted of a wooden beam mounted underneath the existing truck. Two bolts were fastened through holes drilled in the center of the wooden beam, and existing holes in the truck (see Figure 3.18). At the center of each beam end, a wood screw with an equal diameter as the wheels was drilled in. The screw was lead through the wheels fastening them to the beam, functioning as an axle. The starting length of the axle was 600 mm which was seen as the maximum possible axle length. The maximum was chosen as the axle at this point was wider than the sled itself. An even wider axle heightened the risk of hitting obstacles and pedestrians. After testing at a given length, the wooden beam would be cut down to a permanent shorter length and re-tested, thus giving it the hallmark of set-based prototyping (see Section 2.5.2). The tests were conducted with the regular trucks as well as the wheelbase and wheel count prototypes (see Figure 3.19 and Section 3.1.6).

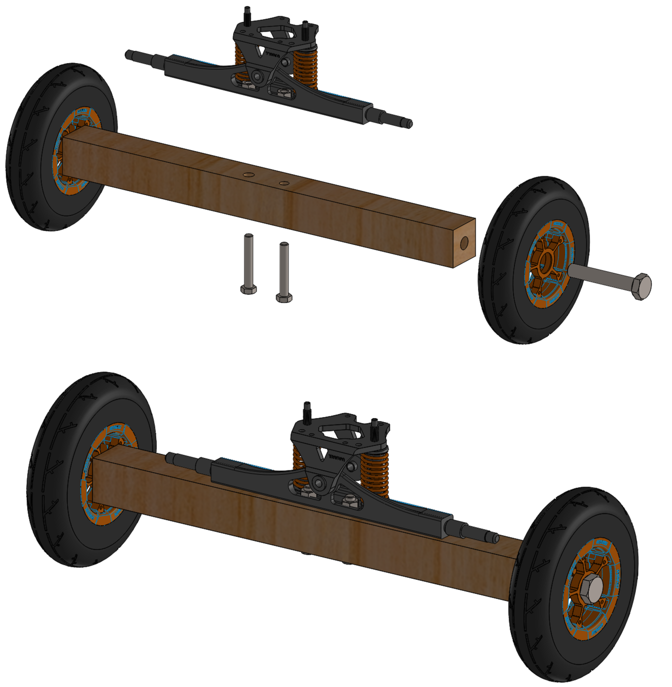


Figure 3.18: CAD created for illustrative purposes

Figure 3.19: Three wheeled set-up with the axle length prototype

3.2.2 Support-Pillows

Planning the prototype

An important part of the seating is the supporting pillows that need to be placed inside. In addition to giving the user enough support, it is a crucial element to prevent pressure ulcers occurring (see Section 2.2). From the authors' previous experience and based on reviewed literature, several materials exists that can prevent pressure ulcers.

Choosing the correct support-pillow material is vital for both Spike and Spear. The products do, however, have different requirements. When operating Spike, the user distributes the weight on both their knees and buttocks, unlike Spear where most of the weight distribution is focused on the buttocks alone. The unique sitting position of Spike relieves the areas of skin usually exposed to pressure due to the knees taking most of the load. The sitting position of Spear, however, is similar to that of a wheelchair which leads to irritation of the same areas of the skin. The pillow material could, therefore, be seen as more critical in the development of Spear.

As it was seen as a manufacturing advantage to use the same support-material in both products the prototyping process would focus on the most critical position of Spear. It would be necessary to uncover possible materials and designs that could prevent the development of pressure ulcers.

The prototype had the following purpose:

- Research and build different solutions with different types of materials
- Select some versions that can be tested out further with a test subject

To be able to fulfill the first purpose of the prototype it was seen necessary to research the types of material used on assistive devices today. This would also uncover how the authors could buy the different materials and their price, which is also a factor to consider. It was decided to go straight for a physical prototype (see Section 2.4.1). It was argued that fast and easy ”cobbled up” prototypes (see Section 2.4.5) would be sufficient for the purposes and easy to test. The idea was to make a couple of different solutions and test the users' experience using Spear. By testing out a range of different solutions the process would have the hallmark of a set-based prototyping approach.

Experimental plan:

1. Research pressure relieving materials
2. Discuss what simple solutions can be built by available materials based on experience, price and popularity
3. Build several ”cobbled up prototypes”
4. Test the prototypes in-house and with users

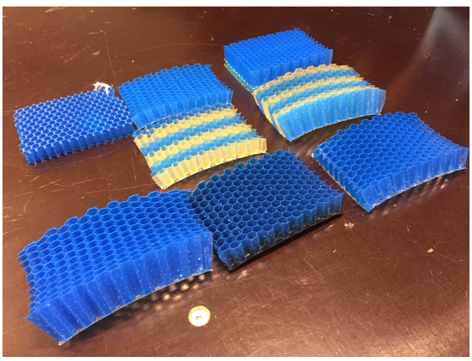
The prototyping process was planned to begin on March 19 with focus on uncovering available materials and come up with possible solutions. The building process would focus on speed and to create the simplest and cheapest prototype possible. This building process was planned to begin on March 26 and be finished the week after Easter, between April 3-6. It was decided to start with in-house testing and then a workshop to get feedback on the solutions that would come up.

Execution of the prototyping process

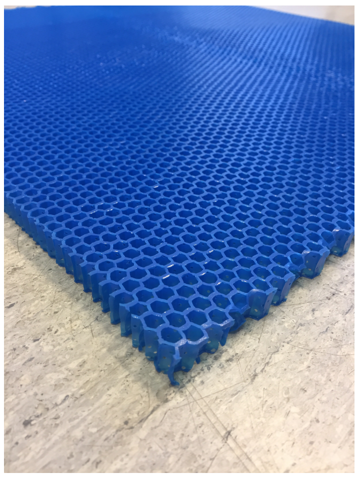
The process began as scheduled at March 19. During the research of pressure relieving materials, one of the authors was invited to Oslo to visit another assistive technology company called Krabat AS. As Krabat focuses on assistive technology for children, they did not see Exero Technologies as a competitor. During the meeting, the author was allowed to experience different kinds of materials as well as learn how to implement them into a design. During the meeting especially two materials were discussed as relevant for both Exeros' products. The materials were memory foam and a gel with honeycomb-structure. This insight also aligned with the theory which showed that slow foam (memory foam), air cushions and specially designed pillows were tested to be suitable to reduce pressure ulcers (see Section 2.2). It was therefore decided to make a solution with each of the three materials discovered. Memory foam was bought at IKEA and rebuilt to fit the current prototype of Spear (see Figure 3.20). The pillow was supported by a hard layer of Styrofoam to get the proper height. The size was based on the current pillow that was already on the Spear prototype. The air cushion was decided to get off-shelf. The authors were able to borrow a few air cushioned pillows from a supplier in Trondheim. This was an air cushion from the company Roho (see Figure 3.21), which is popularly used in several wheelchairs. The air cushion would be placed on the same styrofoam layer mentioned above. This was done to create enough stability and support. The last material was a specially designed product made to reduce pressure ulcers from a supplier called Rehabshop. One of the authors visited their office in Oslo early in the spring of 2018 and discussed the plans with an expert on the field. Rehabshop presented several products with different thickness and structure. To gain more insight into which product to choose, a couple of samples were brought back to Trondheim (see Figure 3.22a). After reviewing the samples and discussing within the team the 12 mm thick SBS-1 was ordered (see Figure 3.22b).

Figure 3.20: Memory foam from IKEA, rebuilt to fit Spear

Figure 3.21: Roho air cushion



(a) Samples from rehabshop



(b) 12 mm SBS-1 pressure reducing pillow from Rehabshop

Figure 3.22: Different pillow prototypes

3.3 Rapid prototyping

Faster prototyping with lower risk is characteristic for rapid prototyping (see Section 2.5.1). At the beginning of this master thesis, Exero bought a Prusa MK3 3D-printer which was heavily used through both rapid prototyping and the building of other prototypes previously described. This section presents processes were rapid prototyping was used as an iterative process for creating prototype-driven specifications (see Section 2.6). It will also cover milestone prototypes created as the last control before ordering major components for manufacturing. Even though a process like this is time-consuming, it was viewed as rapid prototyping compared to the slow process of ordering from a manufacturer.

3.3.1 Iterative rapid prototyping processes

Iterative rapid prototyping processes cover processes were rapid prototyping was used in an iterative process, creating prototype-driven specifications. The processes consisted of creating analytical 3D-models fast and test them quickly with the use of 3D-printing. Many of the Spike parts were already late in the development process such that rapid iterative prototyping would give minimum new knowledge. There were, however, a few exceptions. As the processes were similar, only the mudguard prototypes will be covered as an example in this thesis.

Planning the prototypes

The main purpose of the mudguards was to prevent mud from hitting the riders. For the mudguards to be functional, they needed to fit on an existing truck not developed by Exero. It would also be focused on creating a visual design matching the product.

The purpose of the iterative rapid prototypes was the following:

- Learn about parts with little previous knowledge
- Learn in a fast and less expensive way.

The general experimental plan for each iterative prototypes was the following:

1. Notice that a part is viable for iterative rapid prototyping
2. Create a rough analytical 3D-model
3. 3D-print the analytical model
4. Perform simple tests
5. Repeat step 2-4 until satisfied with the specifications

Iterative processes are spontaneous, fuzzy and hard to plan in detail. A detailed schedule was therefore not created during this prototyping phase.

Execution of the prototyping process

The mudguard was printed with different designs and then mounted on the Spike prototype. The main challenges were to create a mounting solution that would fasten the mudguards securely to the axle. Another challenge was to make room for the brake blocks. A total of 10 different mudguards were designed and printed (see Figure 3.23 and Figure 3.24). Some were rejected quickly due to mounting issues while others were rejected during short-term testing. The final mudguards were testing during Wings for Life (see Section 4.6.2). Through the process, a design was created from concept to pre-production prototype.

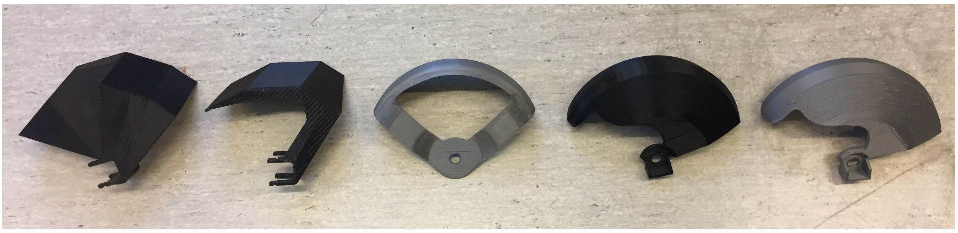


Figure 3.23: Five of the ten 3D-printed mudguards

Figure 3.24: The final 3D-printed mudguard

3.3.2 Milestone-prototype 3D-printing Spike

Planning the prototype

Near the end of this master project, Spike had been developed as far as ready for manufacturing trials. During development, an analytical prototype had been built piece by piece and was now seen as ready-for-order (see Figure 3.25). The design demanded several tooling costs for extrusion of custom aluminum profiles, molding of plastic parts, etc. It was therefore seen as a high risk going directly from an analytical 3D-model to ordering a physical product. To reduce the risk, it was decided to 3D-print the whole sled as a final prototype. The prototype would work as a milestone prototype and also be used to inform the non-developers on the Exero team (see Section 2.4.2). During the high pace development towards the end of the project, a knowledge gap had occurred between the development team and the business team within Exero.

The prototype had the following purpose:

- Work as a milestone prototype to present to non-developers within the Exero team
- Discover faults that may have been difficult to spot on the analytical prototype

Experimental plan:

1. Finish the analytical prototype and extract the necessary files.
2. 3D-print the remaining parts of Spike
3. Assemble Spike while looking for flaws and assessing assembling difficulties
4. Inspect Spike for flaws possibly ignored in the analytical prototype
5. Present Spike and its functions to the whole Exero team

The analytical prototype was planned to be finished at May 25. The necessary data files would then be created, and 3D-printing would begin. The whole printing process was roughly estimated to take 200 hours. It was believed that it would be possible to print non-stop and finish on June 3. The assembly process and inspection would take one day during June 4. A presentation to the Exero team would occur the day after assuming no critical flaws were to be discovered.

Execution of the prototyping process

Exero Technologies had bought their own printer which was heavily used for this prototype. The whole process was slow, which led to parts being printed 24 hours a day. The largest parts were printed in several small pieces and then glued to together due to the limitations of the 3D printer. Except for some minor delays with some of the prints the process went as planned. All parts were mounted together on June 5. The weight of the whole sled weakened the glue, which made it necessary to take the model apart and reinforce certain areas. It was then strong enough to hold its own weight, but not strong enough to withstand any external force. It was, therefore, essential to handle the model with care during transportation and presentation. The finished analytical prototype and the 3D-printed prototype can be viewed in figures 3.25, 3.26, 3.27 and 3.28.

Figure 3.25: Analytical rendered Spike prototype

Figure 3.26: 3D-printed Spike prototype

Figure 3.27: 3D-printed prototype viewed from the side

Figure 3.28: Analytical Spike prototype viewed from the side

Chapter 4

Method: Testing

The following chapter presents in detail how the testing was performed during this master project. It focuses less on the prototypes involved and more on the testing methodology.

4.1 Test subjects

The following section presents the test subjects that were tested with during this master's thesis. The requirements presented by NSD (The Norwegian center for research data) made it necessary to decide whether the testing was going to be reported as quantitative or qualitative data. To fully understand each testing procedure it was argued that a qualitative description of each test subject would be necessary. The subjects' disability, physiology, activity level, age, etc. all affected the testing. The following section, therefore, describes each test subject in some detail. To protect the individuals, each subject is only presented with what is seen as necessary information for the thesis and according to the NSD standard of anonymization.

4.1.1 Test subject 1

Age group: 20-29 years
Gender: Male
Activity level: Very high

Test subject 1 has the condition Cerebral Palsy (see Appendix A, 2.3.2). He is used to a high activity level and has tried a lot of different activities, such as hand cycling, cross-country sit-ski and strength training. For him, training is a lifestyle, and this is shown in both nutrition and equipment. For him, it is important to have reliable equipment which is durable and has a sporty and cool design.

4.1.2 Test subject 2

Age group: 50-59 years
Gender: Male
Activity level: Former Paralympic athlete

Subject 2 has thoracic spinal chord injury. He is paralyzed from the waist down and uses a wheelchair for mobility. He is used to a high activity level and has participated in several Paralympic games. His main competitive sport is cross country sit-skiing. He also practices strength training, downhill sit-ski, and hand-biking. Due to several surgeries, he cannot bend his knees, and therefore can not use Spike as it is today. Instead, he was given the Spear prototype during the pre-masters project (Appendix A). For him, it is essential to have reliable equipment which is both safe and easy to adjust for different activities.

4.1.3 Test subject 3

Age group: 15-19 years
Gender: Male
Activity level: Medium

Test subject 3 has thoracic spinal chord injury. He is paralyzed from the waist down and uses a wheelchair for mobility. He has consistently been training to be as functional as possible with his condition. While doing so, he has been introduced to various types of activities. Subject 3 wishes to have a broad selection of solutions to stay in shape. As a young adult, he is concerned about design and looks of the equipment.

4.1.4 Test subject 4

Age group: 20-29 years
Gender: Male
Activity level: Medium

Test subject 4 has lumbar spinal chord injury. He has reduced mobility and is depending on a wheelchair in his everyday life. He can walk small distances and needs to exercise to keep the mobility from fading. Test subject 4 is eager to try out new things and has among other things been doing wheelchair basket, hand-cycling and cross country sit-ski. Today he has both a three-wheeled wheelchair and a sit ski with roller-skies to train with ski poles during the summer time. For him, the most important factors when considering equipment are safety and adaptability.

4.1.5 Test subject 5

Age group: 15-19 years
Gender: Male
Activity level: Professional athlete

Test subject 5 is born with dysmelia, a malformation of a limb or limbs due to a disturbance in embryonic development. The condition has led to him having one leg which is half the length of his healthy leg. In everyday life, he uses a prosthesis to be able to walk as normal. He has a very active life and has tried most of the activity equipment available to him. Sled-hockey has become the main activity for test subject 5, and he is playing at the professional level. For test subject 5 it is essential to stay in shape and perform optimally in his sled-hockey career. For exercises in the summer season, he now uses a wheelchair with ski-poles for training outdoors.

4.1.6 Test subject 6

Age group: 20-29 years
Gender: Male
Activity level: High

Test subject 6 has a thoracic spinal chord injury. The injury makes him unable to use his legs but he is capable of controlling his abdomen. He uses a wheelchair for mobility in everyday life. The sport he is most passionate about is cross-country sit-ski. Becoming better at sit-skiing is also his motivation when exercising during the summer. Then he uses a three-wheeled wheelchair A. This different sitting position makes it hard to perform early in the winter-season when he is not used to his sled. This is what made him want to test Spike.

4.2 In-house testing

In general, most of the prototypes built by the authors has been tested in-house at some point. In-house testing considers in this thesis, testing that has been occured with only members of Exero Technologies present. The first tests was often conducted in-house to check that everything is made correctly. In some cases, in-house testing was sufficient to fulfill the prototypes' purpose. For example in early-stages where broad ranges of concepts are thought out. During these stages, in-house testing can ensure the quality of prototypes before showing potential users, investors or other stakeholders. This is backed by Elverum (2017) which express that it is essential to consider the audience that will see the prototype, *"Never show fools unfinished work"* [19]. By this, he means that low fidelity prototypes can be misunderstood by an audience that might have expected something more completed. The following section describes some examples of in-house testing that were performed during this masters' project.

4.2.1 In-House Testing 1

Preparation and planning

The wheel count, wheelbase and axle length prototypes (see Section 3.1.6), were initially planned to be tested directly with a user with no prior in-house testing. At the day of testing, however, the user canceled due to a sudden illness. Instead of canceling the test it was decided to perform an in-house test instead. The purpose of the testing was to discover which of the different settings that would be optimal for Spike. Observation and thinking aloud among the authors were chosen as the information gathering methods during this session.

The test had the following purpose:

- Test how different setups affect the steering response
- Measure turning radius with each setup

Testing procedure

The testing of these prototypes was conducted during two different sessions. February 15 the authors took the Spike prototype to Leangen Icehall to get an initial feeling of the different setups. These different setups that were tested were the following:

- Setup A: Regular channel truck in the rear the maximum axle length in the front. Tested with different wheelbases (see Figure 4.1)
- Setup B: Small skateboard truck in the rear and the maximum axle length in the front. Tested with different wheelbases (see Figure 4.2)
- Setup C: One wheel in the rear and the maximum axle length in the front. Tested with different wheelbases (see Figure 3.16a)

Figure 4.1: Normal truck back and increased axle length in the front

Figure 4.2: Small truck back and increased axle length in the front

On March 8 the authors took the Spike prototype with different setups outdoors to measure turning radius. One of the authors were chosen to observe and measure while the other operated the Spike prototype. Keeping the same test pilot on each measurement contributed to the repeatability of the testing procedure and to make the results comparable. The test location was in a parking lot (see Figure 4.3) where each setup was assembled, mounted and the turning radius measured.

Figure 4.3: Test site for in-house testing

4.2.2 In-House Testing 2

Preparation and planning

The truck angle adjustment prototype (see Section3.1.5), was decided to be tested in-house by the authors. As mentioned earlier, it was unclear which angle of the trucks that was considered most optimal. Observations and thinking aloud would be used by the authors to gather information.

The test had the following purpose:

- Test how different angles affect the steering responses
- Decide an optimal truck angle

Testing procedure

March 8 the authors took the Spike prototype with the truck angle adjustment outside to test out different angles. One of the authors were chosen to observe and measure and the other to use the prototype. The goal with this was to achieve the same parameters each time by keeping the same test person. The test was conducted on a parking lot where each angle was adjusted and the turning radius measured. Figure 4.3 shows the place the test where conducted.

4.3 Long-term user-testing

By long-term user-testing, the authors refer to test subjects that have received a prototype to use on their own for testing over a longer period. During the delivery of the prototypes, they were adjusted to the users' needs. During the testing period, the users have given continuous feedback on how the product could be improved. The test subjects have been eager to help and test out different solutions and are considered as helpers or ambassadors for Exero Technologies.

4.3.1 Test subject 1

Preparation and planning

Test subject 1 was introduced to Exero Technologies through the first person that tested the prototype during the authors' bachelors' project. In April 2017 the first test with subject 1 occurred. The location for the testing was Trondheim Spektrum, and it was quickly discovered that the test subject had extraordinary physical strength and endurance. After several tests the following months the subject presented his wishes to either buy or borrow a version of the Spike prototype. Exero saw this as an excellent opportunity to get more feedback and therefore built an additional prototype for the test subject. Since the fall of 2017, the subject has been using this prototype regularly whenever the weather condition would allow for it.

During the period of testing with test subject 1 several test methods were planned, such as usability testing, observations, questionnaire, thinking aloud and focus groups (see Section 2.3). It was planned to get regular feedback from the test subject through telephone calls and Facebook Messenger. Each test session was planned to have a different focus on different types of test methods. Hopefully, the more extended period of time would increase the value of feedback received from the test subject.

The test period had the following purpose:

- To see how Spike would work during a longer period of testing
- Test how Spike will work outside the direct use, how to transport, store and maintenance etc.

Testing procedure

After the delivery of the prototype, several tests and conversations were conducted between the authors and the subject. The subjects access to its own prototype created a constant stream of feedback regarding problems as they were discovered. This feedback allowed for quick responses in the development process. The communication mainly occurred either by phone or chat. Especially the chat option seemed to lower the threshold for the amount of contact the subject would initiate. This added to the amount and how often feedback was given from the subject. During the testing period, the subject also began making his own adjustments to the prototype. Adjustments like mounting a water bottle holder and mounting on a reflective pennant. As the subject went through the trouble of making these adjustments, it was viewed as features required by the user. These types of features were valuable as they were not previously thought of by the development team. The ideas for such features had a clear origin in the subjects ability to use the prototype in the subjects' natural environment. In the early spring of 2018, the authors also visited subject 1 to inspect and perform changes to the prototype. This is reviewed further in section 4.6.1 "Workshop in a users' environment".

> *"I would use this in my daily training. I used the Exero Spike prototype in a race, and it worked perfectly. I would love to buy an Exero sled."*
>
> (Test subject 1)

4.3.2 Test Subject 2

Preparation and planning

In August 2017, test subject 2 made the initiative to contact Exero Technologies through their Facebook-page. He had heard about the company and Spike through test subject 1. Test subject 2 was the first athlete in contact with Exero, not able to use a sled with a knee-sitting position. At the time of contact, Exero already had plans of making a version of Spike with a different sitting position in the future. As the subject was eager to try a new concept, the plans where pushed forward and a simple prototype was created during the pre-masters' project (see appendix A).

As with test subject 1 also this test subject was planned to do the same test methods such as usability testing, observations, questionnaire, thinking aloud and focus groups (see Section 2.3). It was planned to get regular feedback from the test subject through telephone calls and Facebook Messenger. Each test session was planned to have a different focus on different types of test methods.

The test had the following purpose:

- To see if Spike could be further developed into a sled with a different sitting position (Spear)
- Retrieve feedback on important aspects to consider with the new version over a longer period of time

Testing procedure

The long-term testing procedure with subject 2 was similar as that of test subject 1. Both the test subjects received their prototypes at the same time and often exercised together throughout the long-term testing. The older and more experienced test subject 2 gave a lot of well thought out feedback. Instead of contacting Exero often and spontaneous with questions, the subject often presented problems together with possible solutions. The subjects' long experience with assistive sports equipment was also valuable for the team. He was able to compare Spike with other products that he had been testing through the years. Some technical background capabilities also enhanced the value of feedback even further. In the early spring of 2018, the authors also visited subject 2 to inspect and perform changes to the prototype. This is reviewed further in section 4.6.1 ”Workshop in a users' environment”.

4.4 Short-term user-testing

This section presents the short-term user-testing performed during this master's project. Short-term user-testing refers to testing with users with a maximum duration of two hours over a maximum of two sessions. Unlike long-term testing, these test subjects were less familiar with the Exero team and had themselves little or no knowledge of Exero before testing. This type of test session focused more on general experience and thoughts on the product in contrast to the long-term users where more specific parts were tested.

4.4.1 Test subject 3

Preparation and planning

Test subject 3 contacted a member of Exero through their Facebook page and scheduled a meeting in February 2018. The Exero members communicating with the subject was not a part of the development team and limited information was passed on to the authors. The main information received by the authors was that the user had a relative high spinal cord injury. The indoor running track at Leangen Icehall was selected as test site due to poor weather conditions outdoors. Tools, parts and a questionnaire were brought along to the test. The session was an example of testing with minimum information and knowledge of the test subject. In addition only observation was planned to be done since the authors didn't know the test subject and how he would handle the situation.

The test had the following purpose:

- To meet a new potential user of Spike
- Discover if people with high spinal cord injury would manage to operate the product
- Test the new width-adjustable seat prototype, assuming enough time and that the test subject could operate the product in a acceptable manner

Testing procedure

At 14. March 2018, the testing occurred at Leangen Icehall, where the subject showed up with a parent. An introduction occurred, and the subject explained that he contacted Exero as he had heard about the company through friends. He then continued with explaining his injury which was a high waist paralyzing due to an accident five years ago. The subject was familiar with the knee sitting sit-skis and therefore the positioning of Spike as well. However, he quickly mentioned that he was skeptical to how he would manage the transition from the wheelchair to the prototype. The seat was specially mentioned as smaller than what he was used to. The way of entering Spike would be to first position the knees, and then fasten the hip. The subject explained that due to his condition he would prefer doing it in the opposite direction. This would require a seat big enough to support the whole body in an upright position before positioning the knees.

Despite the concerns, the test subject wanted to give the seat a try. With help from his parent, he managed to transfer from the wheelchair and into the sled. The authors observed that the injury led to the subject having less mobility compared to experience with previous subjects. When the subject tried to enter the prototype, it became clear that the seat was too small and not suitable to support the body when entering. The seat was not able to support the body until the knees could be correctly positioned. The testing therefore ended shortly but continued with discussions. The subject was still positive to the concept, and the authors then encouraged thinking aloud about possible improvements. After some discussion, the parent also tried Spike and was positively surprised by the comfortable sitting position. She expressed that she thought this would work for the test subject as long as the seat is improved for mounting.

The feedback was more specificly that the subject would need a seat with more depth and two sets of clamps instead of one. Higher support in the back would also be preferable. The test subject also explained that he was used for getting help when mounting other types of assistive devices and made the following statement:

> *"The best sitting positions is often the ones that are difficult to get into. I like to sit tight, but this often makes the transition from the wheelchair difficult"*
>
> (Test subject 3)

4.4.2 Test subject 4

Preparation and planning

This test subject had met members of Exero several times previous, mainly at different assistive technology events. He had previously tried the prototype two times, during an activity camp at Valnesfjorden, and during an activity day hosted by NAV. Both times were under hectic conditions and in short duration. He had, therefore, several times presented his interest in testing the prototype further. Testing was therefore scheduled in May with a more relaxed atmosphere and more time at hand. The test site would be the parking lot outside Leangen Icehall. Tools, parts and a questionnaire were brought along to the test. The session was an example of testing with sufficient information and knowledge of the test subject. Since the authors were familiar with the test subject, both observations and thinking aloud were planned to be done. Being one of the latest tests in the master's project, the authors made an extra effort to be well prepared and do anything to conduct the ”perfect” test based on experience from previous tests.

The test had the following purpose:

- To meet a new potential user of Spike to find out if his disability could manage the product.
- Test out questionnaire as a method for evaluate the test
- Get feedback on new belts and the latest design concept of Spike

Testing procedure

At May 21 the two authors met the test subject at the designated location. As all parties had met several times before, the conversation quickly became about ideas for changes the subject had thought out after the last testing. As there were two authors present, one was able to converse with the subject while the other prepared the prototype. After making the appropriate adjustment, the subject moved himself from the wheelchair to the prototype. Due to the subject functionality and mobility, the subject was able to perform the transition without any problems. The test then proceeded with the subject trying the sled with different truck adjustments. The springs in the front trucks and back were tightened in the different positions. The effect of only adjusting the front truck was also tested. After trying out several settings and combinations, the subject was asked to move around in a part of the location consisting of cobblestone. The subject explained that this was something he had not been able to do with his current sit ski roller-skies. The authors used observations in combination with conversation and ”thinking aloud” during the test. It was easy to communicate with the test subject, and he pointed out several things that could be implemented in the final solution. The final part of the test was a questionnaire (see appendix B, B-6), where the test subject was asked eleven questions with a score from 1-5. During this questionnaire, the test subject was shown renderings of the final product (see Figure 4.5 and Figure 4.6) and asked about his opinion. The session ended with a plan of meeting again when the final solution was ready.

> *“When you are ready with the final solution I will return my current sit-ski and apply for Spike. This product is far more versatile”* (Test subject 4)

4.4.3 Test subject 5; Test 1

Preparation and planning

Test subject 5 was contacted by Exero in the fall of 2017. The authors became aware of the subject through one of the physiotherapists at the Centre for Elite Sports Research in Trondheim. Only one author would perform the testing procedure. This was deliberate to explore potential advantages or disadvantage of having a single author compared to having additional authors present. The plan was to observe and take pictures during the test as well as to make a summary the thoughts and suggestions for further work, presented by the subject.

The test had the following purpose:

- To meet a new potential user of Spike to find out if his disability could manage the product.
- Get feedback from a professional sled-hockey player on how Spike could be used in context with sled-hockey training.

Testing procedure

The testing occurred on September 3, 2017, at NTNU Gløshaugen. The test subject was very positive before he tried the prototype and expressed that he liked the concept. It was, however, a challenge to adjust the sled due to the subjects shorter leg (see 4.1.5). Some foam material was therefore added underneath the smaller foot to match the subject's physique. Due to a smaller leg affecting the weight distribution, the truck springs were adjusted independently to compensate (see 2.1). All the adjustment necessary occupied the author and led to some waiting time for the subject. When the adjustment was completed, however, the testing could begin. Now the author could fully focus on observing and interacting with the subject. The author also made some attempted to take some pictures, but with poor results as the focus also had to be on the safety and comfort of the subject. From the authors perspective, it was a bit hectic and challenging to have an organized approach to the test session. Doing several tasks simultaneously made it difficult to both document and interact with the test subject satisfyingly.

The feedback was in general positive. He could easily see how this could help him improve strength and mobility for sled-hockey. Because of his interest in physiology and training, he suggested a new test with the final solution of Spike, where we could test how much of the upper body that is activated with this type of movement. It was also decided to do a more thorough test at one of his training session with the team.

> *"This feels a lot better than my wheelchair today. It could be exciting to see how much more I can use my abdominal with Spike than the wheelchair"*
>
> (Test subject 5)

4.4.4 Test subject 5; Test 2

Preparation and planning

After the first test at NTNU Gløshaugen, it was decided to do a follow-up test on the same subject at one of his training sessions with the sled-hockey team. The session took place outside of Leangen Icehall. The purpose was to explore possible benefits of testing in the environment of a professional training session. It was assumed as beneficial as both the coach and other athletes would be present. The authors, therefore, planned to encourage ”thinking aloud” in the group as much as possible. For the same reasons as the first test, only one author would lead the testing procedure. The author would have no focus on interactions but instead, observe how the prototype would be used in this environment.

Testing procedure

14. September 2017 the author showed up at Leangen Icehall and met the test subject along with his trainer and one of the other teammates. Both the trainer and teammate had heard about Spike and inspected it thoroughly. They seemed to like the concept and was excited to see how it would perform in the training session. The session consisted of several 100 m hill intervals. The test subject seemed to have more control regarding steering, as the athletes in a three-wheeled wheelchair (see Appendix A) had to switch between poling and steering the third wheel. The author observed that while the test subject in the prototype achieved a higher speed upwards the hill, he achieved a lower speed on the way down. During the session, the author talked to the coach about the training program of the sled-hockey players. The coach gave valuable insight into the demands of Spike seen from the point-of-view of sled hockey athletes.

The feedback was again very positive from the test subject. He told that he performed better with Spike than his regular training wheelchair when climbing the hill. He was used to be beaten by his teammate, but this time he followed him better. It was still a little bit hard to get used to the sled, but he felt an increase in control this time compared to last time. The possibility to use more of his upper body when using the poles were again mentioned and was also backed by the coach, who saw a potential benefit with the increased range of movement with Spike.

4.5 Workshop

A workshop can in this regard be seen as a focus group with the intent of bringing new thoughts and experience into the product development team. Compared to focus groups the workshop is more focused around active elements that leads the conversation. The activity can consist of sketching solutions, testing prototypes, etc. This section presents the workshops held by Exero and the author during the masters’ project.

4.5.1 Seat-workshop

Preparation and planning

The purpose of the seat-workshop was to get feedback on the current prototype of the seat (see Figure 3.2) and the use of memory foam (see Section 2.2). This part of the product was considered to be one of the most critical and the development team wanted to ensure valuable insight. It was theorized that a calm setting of several motivated users would give more knowledge compared to short tests. As the seat needed to be designed while avoiding pressure ulcers, a physiotherapist was invited as well. Even though Exero had some knowledge on the subject, a physiotherapist would be able to indicate the medical side of the solution. There are also physiotherapists deciding if users are allowed to receive different assistive equipment in the NAV system. It is, therefore, crucial to develop equipment that is seen as valuable from their point-of-view. Two test subjects were also invited to provide first-hand experience with the problem. It was planned to encourage as much thinking aloud as possible in addition to observe how the participants discussed the topics.

In the literature, it is mentioned both benefits and disadvantages of involving people outside the product development early in the process, [19]. The authors considered this as a good opportunity to test out how that could affect the process. It would also be interesting to see the users reaction to discussing solutions in the presence of a physiotherapist. This was also the first workshop held by Exero, and it was interesting to find out if this could be a valuable method to continue with.

The main purpose of the seat-workshop was the following:

- Show, test and get a first impression of the seat from two potential users and one physiotherapist
- Discussions of the participant's previous experience with seat and pillows
- Encouraging thinking aloud about potential solutions that could be developed further
- Observing the interactions between a skilled medical worker and users within a group

Testing procedure

The workshop took place on 13 November in the Exero office at NTNU. Attending from Exero were one of the authors and an additional member of the team. The participants were test subject 1, test subject 6 (see Section 4.1), and a female physiotherapist from St.Olavs Hospital. None of the participants had previously met.

After a brief introduction, the workshop began by presenting the different prototypes that would be discussed. The participants were encouraged to observe the prototypes and present feedback even before testing. The amount of discussion was however low, and the Exero team had problems retrieving feedback and keeping the conversation going. Even when actively encouraging the users to explain their thought, the feedback was brief. This phase of the workshop lasted for about 15 minutes. The seat-prototypes with memory foam were then assembled to the Spike prototype. Each participant (physiotherapist included) was then asked to test.

Test subject 1 which had used the Spike-prototype several times before was first out. While actively handling the prototype he opened up and presented a lot more feedback than previous. This lead to the others participating in the discussion as well. Knowing test subject 1 from previous testing, the Exero team observed that he presented feedback in a more thought out fashion. The team was used to him being open and presenting every thought that came to his mind. After the workshop, the team discussed that the presence of a professional health care worker might have heightened the perceived seriousness of the workshop.

The test was continued by test subject 6 and the physiotherapist trying out the prototype. Compared to the test subjects, the therapist presented the feedback as ”demands” rather than ”ideas”. She focused more on features necessary for the product to be recommended by her as a professional.

The workshop lasted for about 2,5 hours, and all participants seemed satisfied with the event. The author got the chance to show all concepts that were planned, and the participants were eager to share their knowledge and opinion about them. They specifically mentioned some possible improvements regarding the geometry of the seat. The set-based with adjustable seat, was positively received by the participant. Both test subjects and the health care professional suggested adding the seat-adjustment as a permanent feature to Spike. They all agreed on the difficulties of being fastened tight enough to excising cross-country sit-ski sleds and believed this could be a valid solution.

4.5.2 Workshop in a users’ environment

Preparation and planning

The workshop was planned as a follow-up inspection on the prototypes given to test subject 1 and 2 (see Section 4.3). As well as performing an inspection, short-term tests would also be performed. Feedback and observations would be evaluated against a short-term test performed previous in the pre-masters project (see Appendix A). As both test subjects had visited the Exero office several times, it was suggested that the author would visit the subjects’ hometown instead. This presented the possibility to observe the subjects in their environment and everyday life. However, it also made the planning for the testing more difficult. In addition to observing, usability testing, thinking aloud and questionnaire were planned to be performed.

The main purpose of the workshop were the following:

- Test and get the first impression from test subject 2 regarding the pillow-prototypes
- Discussion of experience during short-term and long-term testing
- Observing and learning about the test subjects everyday life

The test would be conducted as a workshop with the two authors and the two test subjects present. The location would be decided by the participants and would be unknown to the authors before the meeting. This made it difficult to predetermine how exactly how the workshop was going to turn out. The following set-up was still planned and scheduled to take approximately two hours:

1. Inspection and maintenance of the prototypes 15 minutes
2. Short-term testing 20-minutes
3. Discussion and feedback of short-term testing 15-minutes
4. Discussion and feedback of experiences during long-term testing 25-minutes
5. Observations of the subjects everyday life at home and the gym 45-minutes

Testing procedure

The testing procedure for the workshop did not go according to the pre-planning. Instead of visiting the subject for two hours as scheduled, the workshop lasted for five hours in total. The first abnormality to occur was an additional participant. The location of testing had been chosen by the participants to be at the home of a parent of test subject 1. This lead to the parent was also joining the workshop. All though not a part of the plan, the parent, with a mechanical background and a passion for sports, was a valuable participant in the conversations. The authors were also informed that during the long-term testing, the parent had often participated by riding a bike next to both test subject 1 and 2. Observing them over such a long period presented a unique insight not previously available for the authors.

During the short-term testing the pillow-prototype was tested on the Spear prototype of test subject 2 (see Section 3.2.2). The subject tested all three prototypes (Roho, see Figure 3.21, Memory Foam, see Figure 3.20, and SBS-1, see Figure 3.22b). All the pillows were first tested while being stationary, then while using the prototype actively. The subject recognized the Roho-seat as he had tested it before with a negative result. Even though the Roho-seat was tested among the other prototypes, it was quickly rejected by the subject. Previous experience had shown that users' thoughts and trust considering a product often predetermine the feedback they may present. For each change of seating the subject had to get out of the prototype, back into the wheelchair and vice versa. The process seemed tiresome, as the subject was paralyzed (see Section 4.1.2). A comfort-score on a scale from one to five, was given on each of the prototypes:

1. Roho - 1
2. SBS-1 - 3
3. Memory foam - 5

After finishing the short-term testing, the authors were invited inside to the home of the parent. All the participants sat around a table in a relaxed atmosphere discussing the users' experience of the long-term testing. During this conversation, the observation of the parent became especially important. The parent had through the testing period observed valuable information that the subjects were not aware of. An example was how the sitting position of test subject 2 had changed during several of his training session due to the pillow. These observations seemed to surprise the subject, further implementing that he was unaware of the fact. On several occasions the parent would also disagree with the comments made by the subject, suggesting that his observations were not in line with the subjects experience.

The authors were then invited by the subjects to visit their regular gym. Here the authors were presented with problems the subjects experienced during their training sessions. While not directly relating to the products of Spike and Spear, it made the authors aware of new problems that could potentially be solved by new products in the future.

4.6 Event testing

Event testing is in this report considers testing at locations with more massive crowds mainly due to other activities present. Such locations give the ability to meet and test with many different users in a short amount of time. The authors and Exero had already some experience with event testing from earlier and wanted to further increase the experience during the master's project by attending two more events.

4.6.1 Ridderrennet

Ridderuka is the world largest winter sports event for vision impaired and disabled athletes [23]. The event is held yearly at Beitostølen in Norway. The week-long event is finished by the main event Ridderrennet which is a cross-country skiing competition.

Preparation and planning

The purpose of attending Ridderrennet was twofold. The goal was both to test with users at the location as well as networking and find users for more thorough testing at a later time. The size of the event makes it a great platform for meeting potential users for testing. There was also a goal to get feedback on the visual design of the product. An event like Riddernnet has a large flow of people which would give many different "first impressions" of the design. At this stage the all-around visual design of the product was close to being finished. As this was the third time Exero visited the event, the team members had some expectations of how it would occur.

Two members of the Exero team (one author included) would travel from Trondheim to Beitostølen the day before the race on March 16. The day after they would assemble a stand near the finish area of the race. Exero had borrowed tent and tables from the organizers on arrival the two previous years (see Figure 4.4). It was therefore assumed, the same would be possible this year. Due to the little advancement of the Spear prototype process, only the Spike prototype would be presented on the stand.

Figure 4.4: Four Exero-members at Ridderennet 2017

To achieve the purpose, the following preparation conducted:

- The Spike prototype was re-built back to an older version. None of the prototypes mentioned in this thesis were brought to Ridderennet. Previous experience had shown that the testing time available with each user was limited to such events. It was therefore assumed that a more well-known version of the prototype would lead to an easier testing process
- The analytical model of Spike was colored and rendered. Rendering is a time-consuming process but gives a much more lifelike impression compared to a sketch (see Figure 4.5 and Figure 4.6). The rendering was created to be able to get feedback on the design
- Informative flyers were created to hand out to people passing by. The flyers contained a simple description of the product and contact information (see Appendix C)
- Sign-up form for people to write down their contact information to able us to make contact at a later date (see Appendix D)

Figure 4.5: Rendered figure of the visual design of Spike (front)

Figure 4.6: Rendered figure of the visual design of Spike (rear)

Testing procedure

When arriving at the location of the race, the team was informed that it was uncertain if borrowing equipment would be possible. This year the organizer had less equipment than usual. By not transporting equipment from Trondheim, the ability to put up a stand was jeopardized. Fortunately, the team was able to borrow a table. However, without a tent with a fastened poster like in 2017, the stand was a lot less recognizable and attracted fewer visitors (see Figure 4.7).

Figure 4.7: Co-Author Mathias T. Berg talking to Diane Hanisch, previous Secretary General of Ridderennet in 2018

As the stand was less noticeable than previous years, the team had to walk around the area and announce the stands presence actively. This action helped the stream of visitors achieve an acceptable level.

> *"I like the sporty look! Who thought assistive devices could look so cool?"*
> (Parent of a young potential user)

4.6.2 Wings for Life

The Wings for Life World Run is a running competition with the aim to collect money to research on curing Spinal Cord Injury. The event is held every first weekend in May and is taking place in around 35 countries. Both runners and wheelchair users are able to participate. The concept of Wings for Life World Run is to be overtaken by a "Catcher Car". The participants get a 30 min head-start before the car and when the car "catches" the participant they are are out of the race. The goal is to get as long as possible before being overtaken. Exero Technologies participated in the event in Stavanger 2017 where test subject 1 used previous Spike prototype. The event was a success and the authors wanted to do a new test in the 2018 version. As there was no actual event in Trondheim, Exero Technologies partnered up with Red Bull and organized a Wings for Life event in Trondheim. In Trondheim, there would not be an actual car, but an app would inform the participant of a "virtual car" following them.

Preparation and planning

All of the potential test users from Trondheim where invited and two of them had the chance to participate. Test subject 2 and test subject 6 (see Section 4.1) were the only participants, and only test subject 2 was equipped with Exero prototypes. Test subject 6 competed in the race using his personal wheelchair. The course was 3,6 km long stretch and consisted of asphalt, gravel road and cobblestone terrain. It had two quite steep hills going both upwards and downwards. The participants would run back and forth the stretch until ”cought” by the car. One of the authors would follow the test subject riding a bicycle. The purpose of this was to get unique observations similar to those presented by ”the parent” during the ”Workshop in a users’ environment” (see Section 4.5.2). The second author would take care of the subjects personal belongings, tools and spare parts, at the starting point. As the course was a stretch, the subject would pass this point several times during the race. The subjects personal goal was to reach 13km before being ”caught” by the car. The test subject was planned to arrive 2 hours before the event. This was to ensure time to prepare him for the rules of Wings for Life and the challenging terrain.

During the race, the authors wanted to observe the performance of the newly developed mudguards prototype and memory foam pillow prototype (see Section 3.3.1 and Section 3.2.2). The pillow was redesigned according to feedback given during a previous workshop (see Section 4.5.2). The test would rely heavily on observations by the cycling author as well as a feedback from the test user after the race. As the subject was eager to achieve a good result, it was decided that he would not be disturbed by questions from the author during the race.

The test had the following purpose:

- Test the performance of Spear in a competition scenario on different terrain
- Test the performance of memory foam pillow prototype during a competition scenario (see Figure 3.20)
- Test the performance of the last version of the mudguards made through rapid prototyping (see Figure 3.24)

To achieve the purpose, the following preparations were made:

- Performing maintenance on the Spear prototype to ensure the safety of the test subject
- Build a new an improved pillow-prototype and mount it to the Spear prototype
- 3D-printing the latest revision of the mudguards and mounting them to the Spear prototype
- Gather spare parts for all crucial elements of the prototype, e.g., wheels and braking fuel

Testing procedure

Before the race, the subject tried the modified memory foam pillow. He was satisfied with the changes and was willing to use the pillow during the race. One author was placed at the start/turning point of the course in order to help the test subject with a 180 degrees turn at the end. This author took pictures and could observe the difference in handling of the sled in each round. The other author followed the test subject on the bike and helped navigate as well being a support along the way. Observation was used to see how the test subject managed different challenges as cobblestone, uphills, downhills and maneuvering in crowds. After the race the authors had a debrief with the test subject and discussed how the session had gone. This led to a thinking aloud session were several thoughts for further improvements were discussed.

During the race, the mudguards worked as intended. They stayed fastly secured throughout the race and prevented mud from hitting the subject. The mudguards were so successful that the design was viewed as finished afterward. The strength of the 3D-printed material also proved high enough, making this a possible way of manufacturing the product.

> *”I am so happy inside. I really do not know how to express it!”*
>
> (Test subject 2)

Chapter 5

Results

5.1 Prototyping

The following section presents the results retreived from each prototype during this master's project. The results are presented in the view on the methodology and not the technical result discovered by the prototypes. The technical results can be viewed in the appendix (see Appendix B). The results are presented through the authors view and experience using each prototyping method.

5.1.1 Set-based prototypes

Width-adjustable seat prototype 1

This prototype was flexible and the set-based nature made it easy to gather the technical results necessary (see Appendix B). The prototype fulfilled its purpose by creating an easy way to measure the hip-variations within the user group. The prototype was tested during the seat workshop (see section 4.5.1) which resulted in praise of the set-based adjustability itself. Based on the advantages this width-adjustability provided, it was decided to implement it in to the design of the product. The second purpose ”discover the number of different seat sizes necessary” was therefore deliberately not fulfilled. The prototype demanded some planning and development as the set-based adjustability mechanism had to be designed. The building itself was simple and was performed with no implication.

Width-adjustable seat prototype 2

The analytical prototype enabled, through its flexibility, to test different concept in the 3D-environment with no material cost. The process was however very time-consuming, especially when concept were scrapped late in the process. This led to delays. When finished, however, the prototype could be combined with existing analytical Spike prototypes. This combined with FEM-analysis reduced the uncertainty in the project. Besides testing the strength through FEM-analysis, the prototype was not tested other than visual inspection. The analytical prototype fulfilled its purpose (see Section 3.1.2).

Width-adjustable seat prototype 3

Prototype 3 was able to recreate the ergonomic shape of seat prototype 2. This was made possible cheaply with the use of 3D-printing. Re-using the mechanical solution from prototype 1 gave the new physical prototype all the functionality as a final product. The authors was able to test the prototype carefully, but not mounted to a Spike prototype. The ergonomic shape had a low strength limit due to the 3D-printing process, which limited the testing capabilities. The shape could however be inspected an further optimized. The prototype fulfilled its purpose partially.

Width-adjustable seat prototype 4

The last seat prototype was created during a somewhat less ”rapid” 3D-printing process. The first print in 1:5 scale confirmed the design and removed uncertainty before more time would be invested in the bigger print. This opened up for changes to be made, and saved resources for the company. The prototype made it easy to inform the non-developers in the company of the progress made during the development process. It was also sent to a sewing-manufacturer responsible for manufacturing pillows to the seat. The manufacturer responded that having a physical version early, eased the process. By discovering flaws, communicating to manufacturers and update the Exero team, the prototype fulfilled its purpose.

Trucker Angle Adjustment

The analytical prototype was designed quickly due to the low complexity of the chosen solution. The delay that occured when creating the physical prototype did lead to some downtime in the project. The prototype worked as intended and was able to produce comparable data sets. By having a set-based prototype the time used to test each setup was relatively short. It was however discovered that the author had to exit the prototype for each adjustment. For a potential future test subject, this would mean a strenuous transition from prototype to wheelchair. This was a clear disadvantage with the prototypes design. The prototype fulfilled its purpose by delivering the technical results necessary (see Appendix B, B-2)

Wheel count and wheelbase prototypes

Using ”cobbled up” prototypes in this prototyping process decreased the cost necessary. Including ”of the shelf” items in an adjustable set-based prototyping design, increased the difficulty and creativity necessary during the development process. The resulting prototype did however fulfill its purpose.

5.1.2 Set-based prototyping

Axle length prototypes

The use of wooden materials made the the axle length prototype a cheap set-based prototyping solution. Instead of creating several solution to create data sets the prototype was instead able to be permanently changed due to the workable material. This made the prototype less flexible compared to set-based prototypes. The method proved to be easy and required minimal planning. The prototype fulfilled its learning purpose by providing the data set necessary (see appendix B, B-1).

Support-Pillows

The support pillows were an example of different ”cobbled up” products that were compared to each other creating a data set. By having the possibility to borrow some of the products it was a relatively cheap way of prototyping. The process required little building from the authors and the ”of the shelf” materials was relatively easy to come by.

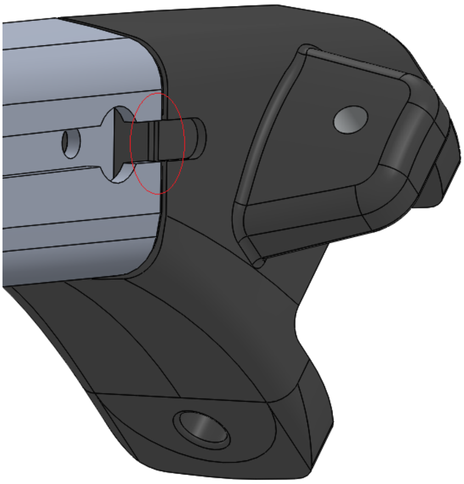
5.1.3 Rapid prototyping

Iterative rapid prototype processes

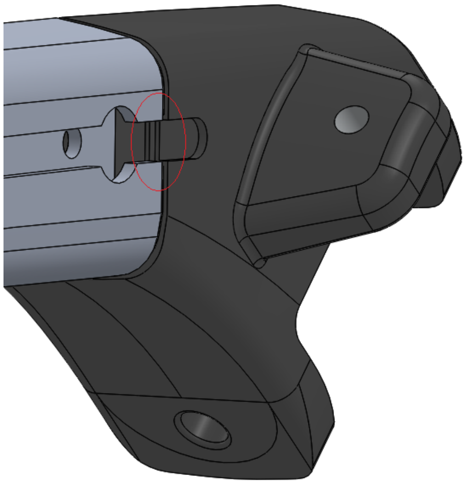
The mudguards give a perfect example of how rapid prototyping could be used in the product development process. The process encouraged creativity and was considered to be a motivating working method. It is a relatively cheap method in addition to being extremely fast compared to traditional production methods. An iterative rapid prototype process was considered valuable with small and less complicated parts of the product. When preparing for production, it was however realized that the final prototype had some manufacturing difficulties. Molding has, compared to 3D-printing, more design limitations and these were not taken into consideration while developing during the rapid prototype process.

Milestone-prototype 3D-printing Spike

The prototype fulfilled its purpose by being a milestone prototype, which communicated the progress within the Exero team and discover pre-production flaws. The 3D-printed version discovered a gap between two of the parts which were not seen in the CAD-model (see Figure 5.1 and Figure 5.2). By making a full-size model, the authors could physically see how it would be assembled. The model was appreciated by the other team members of Exero Technologies as it gave them the opportunity to see how the final design would look like. The process took a bit longer time than expected and required a lot of work due to the size of the print.

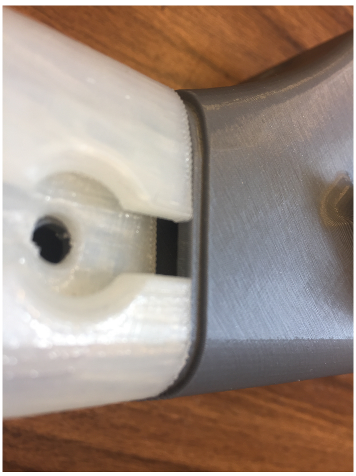


(a) The gap, hardly shown on the analytical prototype



(b) The analytical prototype re-designed

Figure 5.1: Pictures before and after the gap was discovered seen in the analytical prototype



(a) With gap between main frame and end-profile

(b) Redesigned without gap

Figure 5.2: Pictures before and after the gap was discovered

5.2 Testing

In the following the sections, the result of each testing procedure will be presented. As with the prototyping result, they are presented with a focus on methodology. All test reports and results can be seen in the appendix (see Appendix B).

5.2.1 In-house testing

In-House Testing 1

The test session was heavily influenced by observations and thinking aloud between the authors. The test was conducted quickly and with no strict structure. This made it challenging to stay focused during the test which led to poor documentation of results. A full test report can be viewed in the Appendix B, B-1.

In-House Testing 2

As with in-house testing 1, observation and thinking aloud was the main information gathering techniques used. During the test, the authors discovered a disadvantage with the angle adjustment prototype, creating unnecessary struggles for a potential future test subject (see Section 5.1.1). Discovering the disadvantage during the in-house testing was beneficial to the development team. It let the authors be aware of the problem before experiencing it with a user. It also enabled the prototypes to be changed before further testing, even thought no changes was made in this case. Experimental results can be viewed in Appendix B, B-2.

5.2.2 Long-term user-testing

Test subject 1

Long-term user-testing with test subject 1 proved valuable through the product development process. It was however resource demanding. It was expected from the subject that the authors performed continuous maintenance on the prototype. Although resource-demanding, it also revealed new problems and features that was not known to the development team prior to the testing. Thinking aloud and usability testing was the most used techniques during this testing. The authors had some communications problems with the test subject along the process which led to some difficulties. Some misunderstanding occurred, some problems were reported late to the authors, as any time of day through private channels. Experimental results can be viewed in Appendix B, B-3.

Test subject 2

Long-term testing with test subject 2 was performed mostly in the same way as with test subject 1. This test subject was older, and the responding feedback was more well-thought out and reasoned. The subject was seen as a ”demanding customer” and seemed not afraid to present negative feedback. Over the course of the testing, the honest criticism seemed to increase as the authors got to know the test subject. Observation was extensively used along with thinking aloud and usability testing. The whole process of long-term user-testing provided important information, which also led to a high resource-demand in both time and money. Experimental results can be viewed in Appendix B, B-4.

5.2.3 Short-term user-testing

Test subject 3

At the beginning of this test session it was discovered that the subject was unable to use the prototype. The session mostly consisted in discussing why the subject was unable to use the prototype. Both the subject and the parent came with possible solutions through a thinking aloud session. This gave valuable insight into how the product could reach larger user-group. From a product development point of view, the test session was considered successful due to the constructive feedback that was received (see Appendix B, B-5). Due to the failed attempt at trying the prototype, the questionnaire was not conducted as planned.

Test subject 4

By having both authors presenting at the test, it was possible to make adjustments to the prototype and keep the test subject active in the conversation simultaneously. Observations were used to learn how the test subject handled the prototype in the authors opinion. After the test, a questionnaire was conducted which was followed by deliberately induced thinking aloud session. The questionnaire was answered with ”unrealistically” high scores considering the state of the prototype, and little constructive feedback was received throughout the session. Experimental results and the answered questionnaire can be viewed in Appendix B, B-6.

Test subject 5; Test 1

This testing session was conducted with only one author present. This made it difficult to both make conversation and adjust the sled at one time. When the test subject started to move around in Spike, the author was force switching focus from observing and interacting with the test subject which made it difficult to take pictures and document the test. Experimental results can be viewed in Appendix B, B-7.

Test subject 5; Test 2

As follow up from the first test, the authors planned a new strategy in this session. The author interacted less and observed more. As the subject handled the prototype better, the author could focus more on observing rather than interacting and helping the subject. This made it possible to document and take pictures along the test. After the training session a group discussion occurred between the test subject, his teammate, and coach. The teammate and the coach then presented their own observations and, as they knew the subject, placed them in the context of previous observations. This led to new information not registered by either the subject or the authors. Experimental results can be viewed in Appendix B, B-8.

5.2.4 Workshop

Seat-Workshop

The workshop was an effective method for receiving feedback on the seat prototype. Gathering several people with a different background, made it easy to conduct a thinking aloud session. It required good preparations from the authors, but the session in itself gave a lot of feedback in a short time. Mixing professionals and end-users made it possible to discuss the use of the product in several ways. The authors experience with the workshop was positive as long the right people are brought together and a well-prepared plan. Experimental results can be viewed in Appendix B, B-9.

Workshop in a users' environment

This workshop was an example of testing out the prototype in the test subjects natural environment. When testing out the memory foam, test subject 2 gave highly positive feedback quickly after trying it out. From the pre-masters project, the authors were aware of how quick positive feedback could be in danger of being an exaggeration (see appendix A). The statement, however, was backed by the parent which through his experience of observing the subject, noticed a significant improvement in the subjects' posture. Test subject 2 then tested the pillow while actively using Spike. While doing so, test subject 1 and the parent actively discussed benefits and disadvantages they saw in the new material. During this process, the authors stayed as passive as possible. Giving them the ability to talk freely let the authors discover the areas which seemed important to the subjects. However, the discussion would also go off topic once in a while if the authors did not intervene. Being approximately 6 months from last testing session with the subject, made it difficult to recognize any major differences on the subjects handling of the prototype. Some improvement was however discovered through using the same questionnaire as during the pre-master project (see Appendix B, B-6). Having a workshop with the test subjects family did also reveal some interesting information that was not thought of before. Experimental results can be viewed in Appendix B, B-10.

5.2.5 Event testing

Ridderrennet

The stand-visitors were mostly interested in talking and hearing about the project, and less interested in testing. Only three visitors tested the prototype. These tests also gave minimal valuable information due to insufficient testing time per visitors and testing on unfavorable snowy ground. Even though few tested, the team came in contact with several potential users that were interested in testing at a later date. An example of this was test subject 4 (see Section 4.1.4).

The rendered pictures got a lot of attention. People were generally fond of the visual design. When encouraged, the visitors would, however, give some feedback on possible changes. The feedback was then constructive mostly about small details and colors.

Several visitors and especially parents of younger potential users expressed delight considering the sporty look of the rendered prototype. The excitement created by the pictures was seen as good marketing for the company Exero. The marketing aspect of the event was a success even though the testing process was mediocre. Experimental results can be viewed in Appendix B, B-11.

Wings for Life

The author that followed test subject 2 with the bike had a unique opportunity to observe how the sled handled different challenges along the track. From the theory, the authors had the chance to observe, think aloud and conduct a usability test (see Section 2.3). From a product development view, it was a great opportunity to see how the sled worked in a competition setting with a high demand for reliability. Another great result of the event is the marketing and publicity that follows and creates more attention from potential test users and buyers. Experimental results can be viewed in Appendix B, B-12.

Chapter 6

Discussion

The following chapter presents different views on the prototyping and testing methods used during this master's project. This is discussed and compared to the authors' previous experience from working in an assistive technology start-up.

6.1 Prototyping

The process of creating set-based prototypes and set-based prototyping are the most comparable methods presented in this thesis. Both methods have through the project showed benefits and disadvantages. Set-based prototypes have generally had lower material costs, but been highly time-consuming. Creating these prototypes demanded development of a modular or adjustable solution, which is not itself a part of the product. This development may be challenging and "steals" time from developing actual features on the product. It can, however, also lead to the discovery of new features implemented in the product as proved by seat prototype 1 (see Section 3.1.1). On assistive devices, the users' disability should also be taken into consideration when developing the adjustability or modular design. During testing of the angle adjustment prototype, the author had to go back and forth from the sled between each adjustment. This would have exposed a potential test subjects to unnecessary struggle and should be avoided.

Prototypes made through set-based prototyping have in this project generally had higher material costs and less time consumption, compared to the set-based prototypes. The prototypes themselves have been easier to design and build. The lack of necessary adjustability or modularity also makes it easy to create sturdy prototypes of high quality. This is important when testing with users, especially long-term. It is, however, necessary to create several similar prototypes to be able to get comparable results. This heightens the material costs compared to set-based prototypes where only one prototype is necessary. Set-based prototyping does, however, open up for easier use of the "cobbled up" prototype technique, as the prototypes are less complicated. This may help reduce the costs to acceptable levels, also for start-up companies.

One way to decrease the costs of physical prototypes is the use of ”cobbled up” prototypes (see Section 2.4.5). By using this prototyping technique in the masters’ project, the authors were able to build cheap physical prototypes quickly and use them for usability testing. This aligns with the findings of Elverum (see Section 2.4.5). A limitation with ”cobbled up” prototypes, however, is that ”of the shelf” items with the correct function may be hard to obtain. If obtainable, and not requiring too much modification, borrowing items may be a way to decrease the cost even further.

The seat prototypes were, in reality, several prototyping steps made during the seat development process. The first prototype was clearly designed with set-based functionality. However, as the set-based functionality was incorporated as a feature in the product, it is somewhat unclear if the following prototypes can be categorized in such a way. The following prototypes had characteristics closer to point-based prototypes answering a simple ”yes or no”-question.

Rapid prototyping has in this project only considered prototypes created quickly through 3D-printing. It has been a fast way to prototype with low costs. This ability makes it a great addition to a start-up company’s agile characteristics. The prototypes can be used to learn, through usability testing, and communicate through milestone prototypes (see Section 2.4.2). The technique has through this project proved itself especially helpful creating pre-production prototypes. The 3D-prints uncovered flaws on analytical prototypes not visible in the 3D environment. As many manufacturing methods demand substantial investments before initiating the process, it has potentially saved Exero Technologies from significant costs. This is especially important for start-up companies with minimal funds to begin with. There are however some elements to be aware of when using rapid prototyping, especially during iterative design. 3D-printers have fewer geometric limitations compared to traditional manufacturing. Designing through 3D-printing, therefore, has the possibility of ending up with a result that is not able to be manufactured. This can turn the advantages of 3D-printing into wasted resources for the company.

Both analytical and physical prototypes were created during this project. Both ways of prototyping showed to have benefits and disadvantages. Analytical prototypes have shown to be flexible with low material costs, concurring with the research presented by Ulrich and Eppinger (see Section 2.4.1). These prototypes can be changed and corrected several times during the prototyping process. While keeping low material costs, creating analytical prototypes may become time-consuming. For start-up companies this is often not an issue as ”working hours” is a cheap resource and ”paid” through ownership in the company. Analytical prototypes also have some limitations considering the kind of knowledge that can be gathered from them. The project has however shown that the flexibility can provide valuable ”cheap” insight, which can later be used when building more expensive physical prototypes. Physical prototypes can be used to perform usability testing (see Section 2.4.1) and, therefore, increases the retrievable knowledge. They have however shown to be less flexible and more difficult to change during the process. Physical prototypes also have a high material cost which is a disadvantage for start-up companies with low funding.

When analytical and physical prototypes are made based on each other, problems may occur. During the masters' project the analytical angle adjustment prototype was created and assembled to an existing analytical Spear prototype in a CAD-software (see Section 3.1.5. A problem occurred however when creating the physical angle adjustment prototype, as the analytical Spear prototype did not match the physical one. Even though the issue in this project was easy to fix, they might in other cases, have larger expensive consequences. To prevent this, the original analytical prototype could be changed after creating the physical one, or all prototypes should be designed directly after measuring the physical prototype they will be assembled to.

6.2 Testing

In-house testing has been extensively used during the product development by Exero Technologies. This type of testing made it possible to confirm hypothesis and thoughts before presenting them to customers or end-users. When testing with users the quality and visual look of the prototypes are relevant, as Elverum explains "do not show fools unfinished work" [19]. When performing in-house testing, the prototyping demands are lower. This saves time and money both during the testing, but also during the prototyping process. The location is also less important as long as it fits the needs of the prototype. During the project, the authors discovered several flaws with the prototypes during in-house testing leading up to future user testing. This saved time as the team was able to correct the prototype before new tests would occur. In-house testing does, however, have a major flaw when testing assistive devices. None of Exero's team members are disabled and therefore not in the user-group. The knowledge gathered by such testing is therefore limited, and a development team can therefore not rely on in-house testing alone. This method of testing also tends to be performed quickly before continuing development. This can lead to poor documentation which makes it hard to compare results in the future.

Two long-term tests and several short-term tests were conducted during this master's project. The long-term testing resulted in large amounts of knowledge previously unavailable to the authors, which is aligned with the research of Bühler (1996) [10]. Testing without the presence of the development team may uncover everyday challenges not present in a controlled environment. Letting the participants store the prototypes at home also gives feedback on others aspect of the product like storage, maintenance and general handling of the prototype. This is a considerable advantage compared to short-term testing. Testing a product over time or at multiple occasions has shown to increase the value of the feedback as the users become familiar with the product (see Section 2.3). It is however a resource-demanding process, which match what Shah *et al.* (2009) have researched [11]. Long-term testing demands higher quality prototypes and to continuously follow up on the participants. Performing long-term testing or multiple tests with numerous participant would be too resource demanding for a start-up company. As mentioned earlier it is necessary to test with a high amount of users due to the variations in preferences and needs. This is where short-term testing plays an important role. While not giving the same amount of knowledge per test, it enables new input from different users with unique preferences and demands. Specific measures can also be made to increase the value retrieved per test. As an example, the authors experienced a considerable increase in knowledge gathered when third-parties were involved (parents, coaches. etc.) and when performing test in the users own environment (Organized training sessions, at home. etc). Short-term testing also works to involve possible future buyers at an early stage. Developing new features based on users feedback can give the subjects a feeling of ”ownership” to the product.

Workshops proved to be one of the most informative processes performed during this masters' project. Workshops can be conducted in a variety of ways, shown by the difference between the ones presented in this thesis. One aspect that differs between the workshops was the relationship between the participants. In the first workshop, the participants were unknown to each other before the session. This created a slow start where some of the participants seemed insecure about commenting the product (see Section 4.5.1). The intensity increased, however, as the participants got to know each other. To prevent the slow beginning, it might be beneficial to start with some structured activities to ”break the ice” early. At the second workshop, the participants knew each other well (see Section 4.5.2). This lead to the workshop having a relaxed atmosphere and led to the participants not being afraid to disagree with each other. As this workshop was at a users home, most of the workshop was out of the authors' control. It is therefore vital to communicate before the session about the purpose of the workshop, and how it preferably should be performed. A general rule might be only to perform such workshops with well-known participants as such communication is difficult with unknown ones.

Both workshops had several users involved. At times it was difficult to involve the different users the same amount, especially during actual testing. This was apparent during the second workshop, were test subject 2 got a lot more attention from the authors. It is important to be aware of this problem as every subject had invested equal time in the workshop and therefore should feel equally involved.

Workshops generally demanded more preparations and structure compared to other testing methods. However, when done correctly it has the potential to be an extremely efficient learning session. This can also be a problem as much information must be received by the developers at all times. It can, therefore, be helpful to record the workshop or having a member of the team focus on only transcribing, while other members are involved in the workshop.

As with the workshops, the two event testings conducted during this master project has entirely different characteristics. What they have in common, however, is the large gatherings of people. They both also demanded a lot of resources and planning. This should be a high priority. When visiting the first event Ridderrennet, poor planning almost prevented the team from fulfilling the purpose of the test. It should, therefore, be carefully considered before each event if enough time and resources are available. Poor planning has the potential of still demanding a lot of resources from the team while giving minimal results. The large flow of people at an event also makes it difficult to perform any valuable short-term testing. It is, however, an excellent tool for promoting the product and to get in touch with new potential users. If the purpose is testing as well, it should be considered to focus on a few users only. At the second event, Wings for Life, the team focused only on a single test subject. This way of testing led to new knowledge for the authors. It also worked as a promotion as other participants at the event saw the product being handled by a user. This way of testing did, however, not lead to meeting new potential users as the Ridderrennet event did.

One of the major challenges throughout the project was to evaluate feedback received from the users. The authors have experienced that the handicap-community in Norway is generally excited and positive towards development of new equipment. Even though this makes it a motivating and rewarding community to work with, it can create complications when receiving feedback. An example of this can be seen in the scores given by the test subject on questionnaires. The high scores given through this master project and the pre-masters project does, in the authors opinion, not necessary reflect the actual quality of the prototype. Many users are unsatisfied with the products available on the market today. This makes it easy to impress the users with thought out solutions. This does, however, not mean that the solutions are good enough and have no room for improvement. It is therefore beneficial to review different feedback from the same subject over the duration of the process. The feedback should be viewed as an input on the direction of the development process, instead of the actual value of the product.

Connecting with the subjects on a personal level has increased the amount of constructive feedback received by the subjects. This might indicate that focusing on a small number of well-known subjects provides more valuable feedback compared to a high number of unknown subjects. It is, however, important to build a productive relationship with the known subject early on. The downside of the personal relationship is that the subject might become afraid of ”hurting the ego” of the developers when mentioning errors in the design. It is, therefore, crucial to inform the subject from an early stage how vital constructive feedback is for the development process. The authors have experienced that repeating the importance at every test session often leads to more constructive feedback afterward. The same result has however not been registered by the unknown subjects. Even though giving less informative feedback, the lesser known subject, is still important during the development of assistive devices. Each kind of disability has different needs, and the same is true for users within the same disability group. This makes testing with a large variety of users important. During these tests, however, the focus of the developers should be on observing the subject rather than the actual feedback.

The channels of communication with subjects were not reviewed previously to this masters' project. The authors have during the project communicated through personal channels (facebook chat, SMS, phone, etc.). While this enabled easy and quick communications, it also prevented the authors from being unavailable when not working on the project. Users participating in long-term testing may experience problems with the prototype and contact the developers at any time of day. This project had only two well-known test subjects performing long-term testing which limited the amount of contact. It is however easy to understand how it might affect the developers' personal life if the number of participants increases considerably. It should, therefore, be considered to only communicate through established non-personal channels.

Third-party participants have during the project shown to be valuable during testing. When they are known to the test subject (coaches, parents, etc.) they have contributed to discussions from a different point of view. They have also detected positive and negative changes that the test subject themselves were unaware of. This correlates with the research by Shah *et al.* (2006) (see Section 2.3). Third-party participants also provide credibility to the feedback given by the subject if they concur. The seat-workshop also had a health care worker as a participant. As the users of assistive technologies all have a medical condition, health care workers have a lot of information to provide. Their expertise is crucial as they have important knowledge not obtainable by either the developers nor the subjects themselves. Assistive devices also have to be screened by health care professionals before the government can buy them and hand them over to users. This means that problems on the ”medical side” of the development will be detected and should, therefore, be detected as soon as possible.

The most used gathering techniques of information in this project were questionnaires, observations, and thinking aloud. The team did not use questionnaires before the pre-masters project. The technique has proved itself as an effective way of comparing individual tests. It is especially helpful when used on the same test subject over time to measure improvements on the prototypes. The questionnaires presented in this project did, however, contain questions describing the product as a whole. Even though the subject may have issues with details on the prototype, they might be satisfied with the overall concept and answer thereafter. Presenting questionnaires with questions regarding details on the product may lead to more informative answers. Making observations already occur naturally by the team without it being a conscious decision. Focusing on *only* observing, however, led to the test subject to act differently compared to when the authors were more involved in the testing. Only observing can, therefore, be used during parts of testing sessions to gather knowledge, not available, when the subject is more controlled by the authors. This practice should not be overdone as the users might become insecure with lack of guidance during testing. As with observations, ”thinking aloud” had previously occurred naturally during testing sessions. Actively challenging the subjects to express their thoughts did, however, lead to a deeper insight into the subjects way of thinking. This insight provided a greater understanding of which parts of the product that was most important to the test subject. This information can be used to allocate resources correctly during a development process. During the project, no apparent downside was experienced by promoting thinking aloud.

During this master project, the authors researched testing methods during testing of their own developed concept. The authors have been working with the concept over the two previous years and, therefore, have a personal attachment to the product. This attachment might have had an influence on the result of each test. This is especially apparent as all the results are based on the authors’ impression of each method. Weighing the methods against each other is a complex process and it is difficult to create measurable or numerical results. The study should be viewed as a qualitative study with few participants. Due to the limitations of the study, the results should only be viewed in the same aspect. To increase the quality of the results, several studies should be conducted preferably by independent researchers and with different products. It might also be beneficial to only focus on either prototyping or testing methods and not combine the two, as this can influence the results.

6.3 Limitations of the study

This project only considered two set-based techniques and rapid prototyping. There are however multiple other prototyping techniques that could provide benefits for assistive technology development. The number of methods researched was limited according to the time and resources available. It was also limited as the project followed a real development case and each prototype had to fit into the development process.

Comparing the different prototyping methods is difficult as each method was used for creating different prototypes. When comparing costs and time consumption it is therefore based on an estimation of what resources the prototypes would have demanded using other methods. This is not scientifically ideal. Future studies should therefore create prototypes with equal purpose using different prototyping methods.

This thesis presents research on both prototyping methodology and testing methodology, regarding assistive technology. Focusing on two different methodologies at once has limited the depth of the research, due to limited resources. It should, therefore, be considered in future studies, to only focus on one methodology at once.

Chapter 7

Conclusion

This thesis has presented different prototyping methods and test methods with the goal of contributing to research in the field of assistive technology development. Several prototypes were created, solving different problems, with the use of different prototyping methods. This was done in an attempt to uncover what prototyping methods that should be used when developing assistive devices within a start-up company. The prototypes were then tested using several different testing methods. The testing was done in an attempt to uncover how testing should be performed within assistive technology development.

Both the set-based prototyping methods presented in this thesis increased the value of the prototyping process. They enabled an agile development style and the use of prototype-driven specification, which is both important aspects for a start-up company. Set-based prototypes demand low material cost, but is a time-consuming to create. The prototypes generally provide less scientific data compared to its counterpart. Prototypes created by set-based prototyping generally have high material cost, but demands low time-consumption. Using this method makes it easier to create sturdy prototypes of high quality which is necessary if users are going to test the assistive devices. Which of the two set-based methods to be chosen depends on the purpose of the prototype and which resource that is available within the company (time or money).

Rapid prototyping has during this project been beneficial for both learning and communication. Early in the process, the method was used for learning fast and cheaply through iterative prototyping. Later in the process it also served as a communication tool through pre-production prototypes. These prototypes also potentially saved costs by highlighting flaws before initiating manufacturing. Additive manufacturing technology has a high flexibility and low costs, which makes it optimal for use in a start-up company throughout the development process.

In-house testing provided minimal development insight during this masters thesis. With no disabled members of the company, the subject could not answer for the user-group. In-house testing is still important, to ensure the quality of the prototypes and to detect flaws in the design early.

Long-term testing continuously provided new knowledge throughout the development process. It is however a resource demanding process which limits the amount of users that can be involved at any given time. The honesty of the feedback given, generally increases throughout the testing duration.

Short-term testing provided less new knowledge compared to the long-term testing. With a lower resource demand however, more users with unique preferences could be involved. This is especially important for assistive technology development. As it is difficult to determine the credibility of feedback given during short-term testing, observations should be the main information gathering method.

Workshops enabled discussions between participant which was difficult to obtain in any other way. It is a highly effective way of transferring information but it does demand some use of resources and planning. Workshops are an easy way to involve third-party participants like health care workers and parents.

Event testing proved less important for the development process, but worked as an efficient marketing technique. It also helped connecting with future test subjects. It is highly resource demanding and it should be considered if the possible value matches the price.

The main information gathering techniques used in this project were questionnaires, observations, and thinking aloud. Questionnaires was a simple method of gathering data, and comparing data over time indicating the direction of the development. Observations added to feedback from the users, and made the developers able to make their own opinion. Thinking aloud as proved to be the most effective method also demanding minimum preparation. While learning the subjects view on a specific point, it also provides information considering the subjects line of thought, making developing easier in the future.

Providing credible feedback has been a challenge during the process. It is important to take this into consideration when choosing test subjects, especially for long-term testing. Involving third party observers like parents, coaches and teammates presents several views and helps increase the credibility of the feedback.

7.1 Suggestion for further work

This thesis only present one test with a health care personnel present. It was planned to perform two additional tests in collaboration with St.Olavs Hospital which had to be cancelled. The effect of involving health care personnel at different stages in the development process should be researched further.

This project only tested prototypes relevant for the start-up company Exero Technologies. This is very limited comparing to the whole industry of assistive technology. More research should, therefore, be conducted on different branches within this technology.

This study was a qualitative study with few participants. To increase the credibility of the results, a larger quantity of tests has to be performed.

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Appendix

Appendix A

Pre-master Thesis

Specialization Project

NTNU
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Department of Mechanical and Industrial Engineering

Mathias Berg & Bendik Fon

Development of assistive sport equipment for Exero Technologies

TMM4560 – Engineering Design and Materials, Specialization Project

Trondheim, December 2017

NTNU
Norwegian University of
Science and Technology

Summary

This project thesis is written for Exero Technologies a start-up company that develops assistive sports equipment in Trondheim. The authors consist of one student at the NTNU School of Entrepreneurship and one student at NTNU Mechanical Engineering, both co-founders of Exero Technologies. The purpose of this project thesis is to do preparatory work for the following master thesis the spring of 2018. The master thesis will be a product development case for Exero Technologies, more specific a sled for training and activity on bare ground. This is done with the aim of developing a new product for commercialization and to contribute to the research in the field of assistive technology.

The authors have in this paper viewed the challenges with Exero Technologies current product, Spike. Several product development methodologies are presented and discussed on the basis of developing assistive sports equipment. During the project, the authors built and tested three prototypes with successful results. One of these prototypes is also given to a test user for further testing throughout the following master thesis. A product demand specification has also been made to give guidelines for the next prototype in the master thesis. It is concluded that the steering and braking system from Spike can be reused in the new version. The main challenges with the new version are considered to be the sitting position and the seat. The following master thesis will continue the work from this project thesis with the goal of a fully functional prototype by the end of June 2018.

Preface

This project thesis is written in collaboration with Exero Technologies AS. The purpose of the project thesis is to give an introduction to the following master thesis and review relevant theory and methods. The goal of the project is to develop a new version of Exero Technologies existing solution for activity and training by people with disabilities.

The project thesis and master thesis are written by two students from two different faculties at NTNU Trondheim. We want to thank our mentors Knut Aasland and Torgeir Aadland for support and advice on the project. It is much appreciated that this project has been made possible as a joint effort between the Department of Mechanical and Industrial Engineering and the School of Entrepreneurship. At last, we want to thank [redacted] for support and feedback during this project.

Trondheim, December 2017

Mathias Berg | Bendik Fon

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

This project thesis is preparatory work for the master thesis, which is a product development case written for NTNU Department of Mechanical and Industrial Engineering. The authors consist of one student at the NTNU School of Entrepreneurship and one student at NTNU Mechanical Engineering (hereafter the authors). Based on literature review the authors will identify methods for product development in addition to gathering relevant data for the master thesis. This is done with the aim of developing a new product for commercialization and to contribute to the research in the field of assistive technology.

1.1 Exero Technologies

Exero Technologies is a start-up company located in Trondheim at the Norwegian University of Science and Technology (NTNU). The company was founded in January 2017 and develop adaptive sports equipment for disabled people. Their vision is to give everyone the same possibilities to live an active and happy lifestyle. Exero Technologies consists of five students (including the authors), three from the NTNU School of Entrepreneurship and two from Mechanical Engineering. The company is now in the process of commercializing their first product and further development of new versions.

1.2 Spike

Exero Technologies is currently developing their first product, called Spike. This is a sled with wheels used for activity by people with disabilities. Figure 1.1 and 1.2 show the current prototype of Spike. The idea of Spike came from a bachelor thesis written for NTNU Centre for Sport Facilities and Technology. They presented a problem that professional paralympic sit-skiers experience today. Sit-skiing is equivalent to Nordic skiing with cross-country skis for non-disabled persons. The athletes within this sport are lacking a good and safe solution for training their sport in the summer season. There are some solutions on the market today, but they are not considered good or safe enough. Most of them are lacking a good system for turning, and brakes were either missing or unsatisfactory.

Figure 1.1: Bendik Fon using a Prototype of Exero Spike

Figure 1.2: Prototype of Exero Spike

The three engineers at Exero Technologies came up with a solution where the user can steer by distributing their weight towards one side of the sled. Disc brakes were also implemented to make the solution safe and users propel themselves by using poles (see figure 1.1). Several versions of the prototype have from January 2017 to November 2017 been tested by 60 potential users. This type of user-oriented product development has resulted in a product that several users have requested leading up to Exero's first sale of a prototype this fall. The next goal is to finish development of Spike and start selling in Norway during the spring of 2018.

1.3 Social benefits

The Norwegian Government's Action Plan for persons with disabilities defines disabilities as follows:

> *"A disability is a discrepancy between the capabilities of the individual and the functional demands of his/her environment in areas which are significant for the establishment of independence and a social life"* (Regjeringen, 2017)

Being disabled can cause several challenges in everyday life. In Norway, it is a priority for politicians to facilitate work and leisure time for people with disabilities. The following statement is taken from the Norwegian Government website:

> *"The Norwegian government wants to improve living conditions for people with disabilities. Despite being disabled you should have the opportunity to participate as much as possible in working life and social life. People with different disabilities should have the opportunity to a meaningful free time and to participate in social arenas. The government will take several steps to realize these goals"*
> (Regjeringen, 2017)

United Nations Human Rights has declared that people with disabilities shall have the possibilities to ensure their human rights and that the society shall enable this [2]. A report from Medtek Norway regarding assistive devices in Norway concludes that there is a need for innovation in this field and that it should be facilitated by new technology [2].

Exero Technologies has so far received a great amount of goodwill and support for introducing an activity solution for people with disabilities. Since January 2017 Exero Technologies have raised 450 000 NOK from Innovation Norway and won 265 000 NOK in different business competitions. This is the result of the joint effort of a hardworking team and an innovative solution. Feedback from users, the welfare service and existing players in the market indicates a need and place for Exero Technologies.

1.4 Assistive technology

Definition from the World Health Organization's:

> *"Assistive technology enables people to live healthy, productive, independent, and dignified lives, and to participate in education, the labour market and civic life"*
> (WHO, 2017)

An assistive device is not a goal in itself, and it is not the only means of solving practical problems. The purpose of the assistive device is to compensate for the loss of function and solving practical problems, and they must be seen in conjunction with other forms of help to the user. Assistive devices have a function as long as they solve problems that need to be solved. It is crucial that the users are motivated to use the assistive device. The department of assistive technology in Norway consider a problem solved first when the user is satisfied with the assistive device and how it works [3].

1.5 Market and segmentation

Every year, there are between 250 000 and 500 000 new incidents of spinal cord injuries worldwide [4]. The numbers of amputees are increasing due to diabetes. In the US, diabetes account for 50% of all amputees. Due to this, there's an increased focus towards innovative solutions for this segment[4].

70 million people in the world sit in a wheelchair [4]. Market research performed by Exero shows that people with spinal cord injuries, amputees, cerebral palsy, polio or other muscle diseases are in the most need for new solutions within adaptive sports. These disabilities account for 3,2 million potential users in the US and Scandinavia. This is Exero's target market the next five years due to the market size and willingness to pay. Exero's beachhead market is considered to be Scandinavia, due to it is unique welfare services, with approximately 50 000 potential users (see appendix **??**, 4.0 Market, and Segmentation).

Within the market described above, there are different degrees of disabilities. Each individual is different, and the market research has shown that activity levels vary greatly. The segmentation is therefore divided in two, based on the user's previous experience with adaptive sports equipment and their level of disability.

1.5.1 Experienced users (15%)

This segment has used adaptive sports equipment, and are familiar with the solutions offered on the market today. It ranges from professional athletes within Paralympic sports, to those who want to stay active on a regular basis. Many of them practice skiing, sled hockey, rowing, and marathons. The segment can handle equipment that requires control and strength in the upper body. Performance and the possibility to explore new activities will be an important aspect for these users.

1.5.2 Novice users (85%)

This segment is less familiar with adaptive sports. They are more skeptical of new equipment and will spend more time getting familiar with it. They seek independence from physiotherapy but need to maintain the functional parts of their upper body. Within this segment, the users are interested in solutions that include them in society, such as joining in on walks with friends and family. Safety and being able to participate in social activities will be important aspects for these users.

1.6 Research Questions

Exero Technologies has achieved much knowledge in the field of adaptive sports equipment since they started. To evolve and survive as a company it seems necessary to expand the product portfolio in the future. The most nearby solution is to make new versions of Spike. Feedback from testing has shown a potential opportunity for expanding the use of the product. The existing solution today make it difficult in some cases to use the product as intended. In general, the sitting position with the knees bend under the body is a challenge for some people. This could be a result of their disability or lack of movement in their lower body. Based on research of existing solutions and feedback from people that have tested the prototype it is desirable with a new sitting position.

The project and master thesis will focusing on product development with the goal of making a sled with a sitting position that increases the number of people that can use the product.

The project thesis will be focused to answer the following questions:

- **R1: Which activities and solutions exist today for people with disabilities in the lower part of the body?**
- **R2: What kind of aspects is required by a new version of Spike?**
- **R3: Which product development method can be used for developing and building a new version of Spike within the requirements?**
- **R4: Is it possible to use the steering system from Spike on products with other sitting positions?**

1.7 Scope

The introductory chapter has presented the need for new and innovative solutions within assistive technology. Exero Technologies and the context of the master thesis have been presented to give the base for the product development task. Chapter two presents the theory that is considered relevant to the product development. Including methods for conducting a product development process, which will give the authors structure for how they can do the work. Chapter three present the methods of how the project thesis is conducted. Including choice of product development and building of prototypes. Then follows results and discussion with the author's opinion. At last, comes a conclusion which gives an overview of further work in the master thesis.

Chapter 2

Theory

2.1 Product development methods

2.1.1 Classic product development

The field of Design Theory and Methodology (DTM) has a rich collection of research results in both industrial and educational applications [5]. DTM has a main focus on the design processes and activities and considers less the product itself. Despite a long record of research within this field, there is no clear definition of DTM. As the research within DTM has been proceeding, it has evolved towards a more abstract and general form. DTM can roughly be divided into the following categories [5]:

- Concrete and general
- Concrete and individual
- Abstract and general
- Abstract and individual

For this article "concrete and general" is the most interesting group. DTM in "concrete and general" covers a wide variety of products. It looks at several types of design methods and gives a general description. In this group, we can find prescriptive design methodologies in addition to more concrete product development goals. Further chapters will take a closer look at some specific methods within this group.

Pahl and Beitz

The design method presented by Pahl and Beitz is one of the most well-known both in industry and education. The model aims to adapt general statements to the requirements of the mechanical engineering design process and to incorporate the specific working and decision-making gaps [5]. According to Pahl and Beitz design is a fundamental part of the life-product-cycle in an organizational respect, as shown in figure 2.1 [6]. The cycle is triggered by a market need or a new idea. It starts with product planning and ends with recycling or disposal when the lifetime is over.

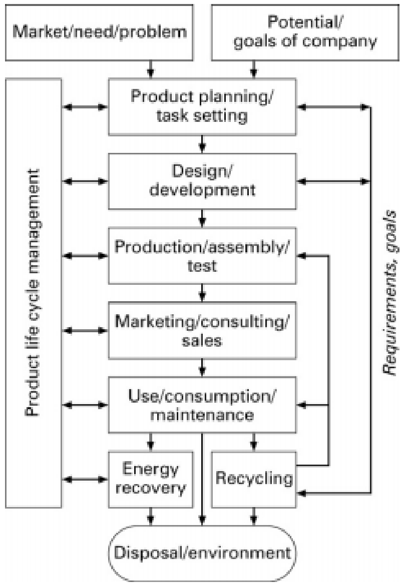


Figure 2.1: Pahl and Beitz's method

Pahl and Beitz split the design process into four main phases [6]:

1. **Product planning and clarifying the task:** The first phase specifies the information that is required. Along with product planning, both requirements and constraints need to be clarified [5].

2. **Conceptual design:** In the conceptual design phase, the goal is to find a principal solution. By doing this, a working structure can be made.

3. **Embodiment design:** includes finding the main structure. During this phase, several alternatives are compared to each other.

4. **Detail design** The last phase is detail design where arrangements, forms, dimensions, and the surface of each part is decided. In this phase drawings and cost estimation are also produced.

Ulrich and Eppinger

The method of Ulrich and Eppinger is well-known when it comes to "modern" systematic design [1]. Their method focuses on product development more than just engineering design [1]. Marketing is also considered in their model in addition to product planning and product definition. Their product development processes are divided into six phases, shown in figure 2.2.
According to the research objectives, the concept development (Phase 1) is considered the most relevant phase. This phase will, therefore, be reviewed further.
Ulrich and Eppinger present a five-step method for concept development (see figure 2.3). The process is not only useful for overall product concepts but also when developing subsystems and specific components [1].

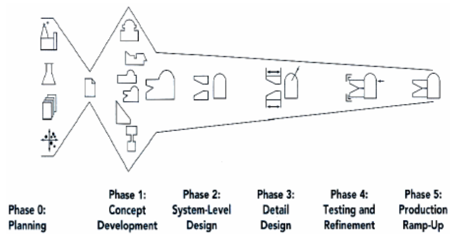


Figure 2.2: Ulrich and Eppinger's model

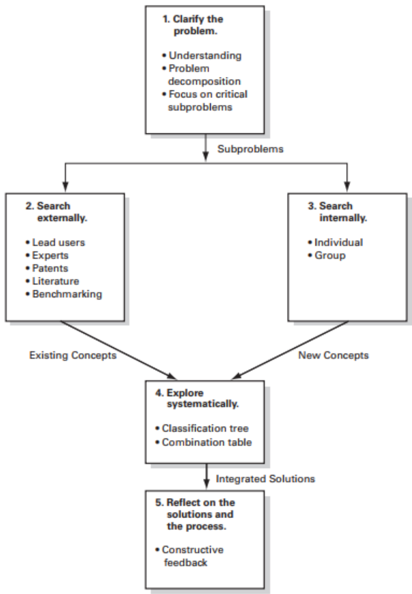


Figure 2.3: Ulrich and Eppingers five step method for concept development

1. **Clarify the problem:** This step consists of developing a general understanding of the problem and breaking it down further into subproblems if necessary [1].

2. **Search externally:** This step is aimed at finding existing solutions to both the overall problem and the subproblems identified during the problem clarification step. While external search is listed as the second step in the concept generation method, this sequential labeling is deceptive. External search occurs continually throughout the development process [1].

3. **Search internally:** Internal search is the use of personal and team knowledge and creativity to generate solution concepts. Often called brainstorming, this type of search is internal in that all of the ideas that emerge from this step are created from knowledge already in possession of the team [1].

4. **Reflect on the solutions and the process:** After the first three steps, the team has col-

lected several concept fragments (Solutions to the subproblem). In this step, the point is to systematically organize these solutions. This can be done by using tools such as the "concept classification tree" or "concept combination table" [1].

IPM Model

The IPM model is based on the Stage-gate model which was developed by Robert G. Cooper in the 1980s [7]. The goal is to manage risk from a business perspective. Stage-gate systems recognize that product innovation is a process. Like other processes, the innovation process can be managed. Stage-gate systems simply apply process-management methodologies to this innovation process [8]. The IPM model is an example of stage gate and is frequently used by students at NTNU, including the authors who used this model in their bachelor-thesis.

The IPM model is divided into five phases. To start a new phase, it is required to reach a milestone from the previous. If the milestone is not fulfilled the phase must be repeated until it is completed. This type of product development reduces resources used and makes it easy to measure progress. The five phases are as follows and shown in figure 2.4:

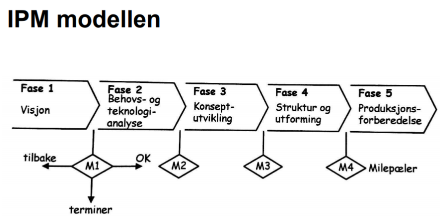


Figure 2.4: IPM-model

1. **Vision:** In this phase it is important to find out if the project is worth doing. From this phase, it is normal to end up with a project description.
2. **Requirement and technology analysis:** In this phase the requirements from customers are considered in addition to investigating competitors in the market.
3. **Concept development:** In this phase several concepts are designed and evaluated. Normal deliveries could be minimum viable products and prototypes.
4. **Test and validation:** In this phase the current solutions is checked up against goal and requirements. Calculations of costs could also fall into this category.
5. **Production start-up:** When all of the previous phases are complete the production-planning can begin. This includes finding the right suppliers and distribution channels.

2.1.2 Agile Product Development

Agile development is a term originally from software development. From the Oxford dictionary is the term "agile" defined as :

1. Able to move quickly and easily [9].

2. Relating to or denoting a method of project management, used especially for software development, that is characterized by the division of tasks into short phases of work and frequent reassessment and adaptation of plans [9].

Unlike the classic product development methods, which have strict plans and stages to complete, agile focus on flexibility and ability to continually adapt to changing environments. The concept of agile development can be documented as far back as the 1950s and from the concept of iterative and incremental development [10]. The modern inspiration for agile came from the work of Takeuchi and Nonaka in 1986 ”The new product development game” [11]. So far it is not an established field of agile development for physical products, but several researchers have proposed possible models [7]. One example is a research project involving Loughborough University and the Central University of Technology, where it is concluded that principles from agile would benefit the development of a physical product [12].

When principles of agile development are adapted into physical product development, it is due to the flexibility and the possibility of responding to changes instead of following a static plan. Thomke and Reinertsen have proposed the following definition of flexibility regarding product development [13]:

> *“Development flexibility can be expressed as a function of the incremental economic cost of modifying a product as a response to changes that are external (e.g., a change in customer needs) or internal (e.g., discovering a better technical solution) To the development process. The higher the economic cost of modifying a the product, the lower the development flexibility.”*
>
> (Thomke and Reinertsen, 1998)

2.1.3 Set-Based Design

Set-Based Design is a methodology that focuses on delaying decisions as late in the development process as possible. It is a way of thinking that can, in some degree, be implemented into different kinds of product development methods. The agile product development methods are especially influenced by the set-based way of thinking. The set-based way of developing focuses on retaining flexibility in the design, which reduces the cost of changes made later in the process. In “point-based design” product development decisions are made as soon as they are encountered [14]. When you hit a path with two options, each is analyzed before one is selected. This way of thinking is time-effective at the beginning of the process, but the need for changes later can become both costly and time-consuming [6]. In set-based design more resources are used earlier in the process to make changes more process-friendly. In practice, this is done by maintaining a set of options further in the process. This set of options is continuously narrowed down until a final solution is decided later as the process continues [14]. The two main principles of Set-Based thinking can be seen as considering sets of different alternatives simultaneously and delaying decisions decision making [15].

As mentioned, the main benefits of Set-Based design are flexibility which leads to lower costs when dealing with changes. It is, however, important to balance the benefit of flexibility compared to the cost of maintaining options further in the process. When working on projects with low uncertainty, a point-based approach might be beneficial as the probability of change is little.

However, on projects with high insecurity, the probability of changes are so high that it can be assumed the cost of maintaining options is less compared to a point-based approach. Another benefit of delaying decisions is the accumulation of information that occurs throughout the process. When decisions are made later with more information, it is a higher probability that the correct decisions are being made[16].

While the Set-Based approach has many benefits, it is a difficult process that requires practice [16]. It is in the human nature to make decisions when it is required of us. Postponing such decision making can create uncertainty and stress. It is the manager's job to ensure that decisions are not mad prematurely [16]. There is also an intervening psychological issue when facing the need for change in development direction. Humans tend to defend their decision after it has been made. This is often done by undervaluing the decisions that were not chosen. The problem occurs when the development team needs to make changes and look at other decisions that were considered. These are now viewed in another mindset compared to when the first decision was made. This can be countered by recording strength and weaknesses of all decisions before one is chosen. This record can be view as a "truth-document" and can be used by the developers to correctly evaluate which solution to try next [16].

Toyota development system

Toyota has been one of the main sources of inspiration during the development of set-based thinking. The term "set-based" was coined by American researchers studying Toyota's design process. However, Toyota themselves does not use the term. They simply see these techniques as a good engineering practice. Toyota's set-based design can be seen as one of the reasons why they experience fewer late-stage changes compared to other competing auto-manufacturers [14]. It is also one of the reasons why Toyota make more clay models of new cars than their competitors do [16].

Toyota focuses on constraint instead of choices. Sets of solutions are narrowed down my discovering constraints that prevent the solutions to become effective [14]. This is an entirely different way of sorting solutions compared to traditional development. However, describing constraints can become quite complex and may, therefore, become time-consuming. Toyota has developed a system to prevent this complexity, called "A3 reports". The goal of this system is to provide accurate information that can easily be absorbed by viewers [14]. The information must be presented simply by using one side of an A3-paper. For this to be possible, the report focuses heavily on graphics which is combined with descriptions in writing [14]. The system focuses on clear thinking, as this is essential to get the necessary information reduced to a single A3-paper. When an A3 report is finished, the author is seen as an expert on the subject. The author will use his expertise by meeting and discussing with other employees who are affected by the topic. These meetings help build a consensus about the decisions taken and ensures that everyone keeps working in the same direction while keeping other options in mind [14].

2.2 Prototyping

2.2.1 What is prototyping?

Prototypes are a commonly used tool when working with product development. A prototype is made to gather information about some unknown elements of the product. Ulrich and Eppinger define prototypes as "an approximation of the product along one or more dimensions of interest" [1]. Prototyping, on the other hand, can be viewed as the process of creating such product [1].

Ulrich and Eppinger argues that prototypes can be classified along two dimensions. The first dimension is whether the prototype is physical or analytically. A physical prototype is built as an approximation to the finished product. It can be used as a proof-of-concept and to quickly test ideas as well as produce the look and feel of the finished product. Analytically prototypes, on the other hand, are usually mathematical or visual. Such prototypes can be used to visualize and analyze a product and are generally cheaper than physical prototypes. Examples of such prototypes are computer finite element analysis and 3D-models [1].

The second dimension focuses on which the prototype is comprehensive or focused. Comprehensive prototypes contain most of the characteristics of the finished product. These prototypes are what most people are thinking of when they hear the word prototype. Focused prototypes, however, considered only a few of the characteristics of the product. As an example, clay can be used to show the shape of the finished product. This type of model is focused as the shape is one of the few insights it provides. Several focused prototypes can be combined, creating a greater understanding of the product [1].

How the dimensions correspond to different kinds of prototypes can be seen in figure 2.5.

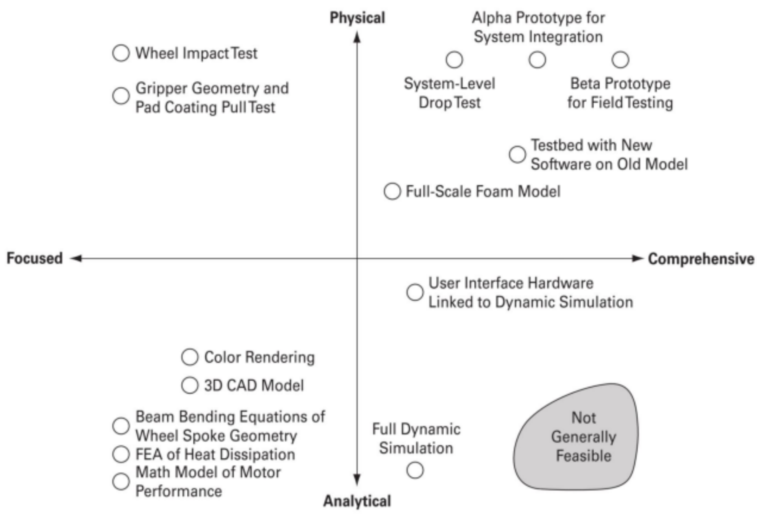


Figure 2.5: Prototypes according to their respective dimensions [1]

2.2.2 Planning the prototype

Prototyping can be a complex work method which requires extensive planning. All prototyping has a cost either it is the price of used materials or the hourly pay of the engineer making a simulation. Without proper planning, there is a risk of ending up with a costly prototype that does not create the value required for the project. Ulrich and Eppinger presents a 4 step way of planning for prototypes to eliminate this threat [1].

- **Step 1: Define the purpose of the prototype**
  Prototypes have mainly four purposes; learning, communication, integration, and milestones [1] The first step of the prototype planning is to decide specific learning and communication needs. This is followed by recognizing any integration needs and whether or not the prototype is going to be one of the milestones in the project [1]. One or more of these purposes can be chosen as the prototypes purpose. This ensured that the cost of the prototypes brings the project further in some way.

- **Step 2: Establish the level of approximation of the prototype**
  This step involves deciding to which degree the prototype is going to be an approximation of the finished product. As an example, a choice that should be decided early is whether the prototype is going to be analytical or physical. As a general rule, analytical prototypes are cheaper, but physical prototypes may produce result unavailable by analytical methods. Generally, it is beneficial to make the prototype as simple as possible while still serving the purpose decided in step 1 [1].

- **Step 3: Outline an experimental plan**
  A prototype can in many ways be viewed as performing an experiment. Regular experimental methods should, therefore, be performed to ensure the maximum retrieval value from the prototype. Such experimental plan should contain the tested variables, a test protocol, measurements that will be performed and a plan for resulting data-analyzing.

- **Step 4: Create a schedule for procurement, construction, and testing**
  The prototype process can be seen as a project of its own. The process is initiated to produce results used further in the general product development process. To get the result within an expected time frame, it is important to also plan the prototype process. There are especially three important events to plan; Finished prototype, First test and Final results.

2.2.3 Rapid prototyping

Rapid prototyping takes advantage of the drastic price drop in prototype production that has occurred the recent years. The 3D-printer is a great example of prototyping-tool that has reduced costs significantly. Rapid prototyping takes advantage of this price drop, not by saving money, but by making more prototypes faster. The method of prototyping highly increases the speed of information collection. It removes the lead time from the equation. The price reduction also makes it possible to start producing cheap prototypes earlier in the process [7].

2.2.4 Set-based prototyping

A problem with many prototypes is the limited knowledge that can be retrieved from them. So-called point-based prototypes are made to answer a simple question; will it work or not. Even though the answer to this question is “yes” or “no” it gives little insight in what could be improved further, or as Christer Elverum describes it “lack of knowledge on optimization”[7]. A way of dealing with this problem is to use the set-based mentality also when prototyping. Instead of making a single prototype, plenty of prototypes should be made to simultaneously to achieve multiple data points and increase the knowledge gathered from the prototyping process. These points of data can be collected and compared in a highly scientific manner. However, this kind of prototyping can become resource demanding. Both building and testing a larger numbers of prototypes steal resources from other necessary parts of a project. Another problem is that the variables being tested by the prototype might be too complex. As an example, set-based prototyping works great when testing the impact capability of a bicycle wheel. However, if the test considers the more complex “feeling” of riding the bicycle, it becomes much harder to achieve valuable results. As a solution to this problem, Christer Elverum also suggests a new term called set-based prototypes. Set-based prototypes can be described as flexible prototypes were the variables can be changed during testing. This kind of prototype may increase the amount of knowledge gathered from each prototype [7].

2.3 Physilogy

Spike was in general developed for people with disabilities in their lower part of the body. More specific people who struggle with walking/jogging/running without any type of assistive devices like wheelchairs, prostheses or crutches. World Health Organization has an international classification of functioning, disability, and health, more commonly known as ICF [17]. This classification looks at functioning and disability in a broader term than just the medical issue. It also takes the social, environmental and daily life into considerations.

For Exero Technologies this will influence the product development. Their product development process needs to take different kinds of disabilities into considerations. Until now they have tested Spike with over 60 different users with a large range of different disabilities. Some of them have handled Spike very well while others have struggled with the sitting position or the transition from wheelchair to the sled. Despite the large range of disabilities it is necessary to start with some of the most common to achieve a systematic approach to the product development process. The following sections describe the disabilities that Exero Technologies consider relevant for Spike and should, therefore, be considered when developing the next version.

2.3.1 Spinal Cord Injury

The term ‘spinal cord injury’ refers to damage to the spinal cord resulting from trauma (e.g. a car crash) or disease or degeneration (e.g. cancer). Numbers from WHO indicates an annual global incidence to be 40 to 80 cases per million population [18]. Symptoms of spinal cord injury depend on the severity of the injury and its location on the spinal cord. This includes partial or complete loss of sensory function or control of arms, legs and/or body. Assistive technology is often required to facilitate mobility, communication, self-care or domestic activities. An estimated 20-30% of people with spinal cord injury show clinically significant signs of depression, which in turn has a negative impact on improvements in functioning and overall health [18]. Misconceptions, negative attitudes and physical barriers to basic mobility result in the exclusion of many people from full participation in society.

World Health Organization have come with measures that need to be taken to implement the UN Convention on the Rights of Persons with Disabilities. One of the essential measures that are highlighted for improving the survival, health, and participation are as followed:

> *"Access to appropriate assistive devices that can enable people to perform everyday activities they would not otherwise be able to undertake, reducing functional limitations and dependency. Only 5-15% of people in low- and middle-income countries have access to the assistive devices they need."*
>
> (WHO -Spinal Cord Injury, 2017)

Spinal cord injury has been a common disability among the users that have tested Spike. Since there is a significant variation of motor control and sensory functions from person to person the results have been very diverse. It is common that these users are dependent on a wheelchair. This leads to a challenge when transferring from the wheelchair and into the sled. Feedback from testing and other manufacturers in the market indicates that this is a common problem. The same problem can also occur with handcycles and sit-skies.

2.3.2 Cerebral Palsy

Cerebral Palsy (CP) is a neurological disorder caused by a malformation non-progressive or brain injury that occurs while the child's brain is under development [19]. By having CP muscle coordination and body movement is affected. An individual with CP will likely show signs of physical impairment. The type of dysfunction will vary greatly from each individual. It can affect arms, legs, and even the face; it can affect one limb, several, or all [19].

As for most types of disabilities, CP is unique to each individual. Spike has so far been tested with an overweight of users with CP, and the first prototype of Spike was also sold to a man with CP. Exero Technologies has experienced less problem for people with CP to transfer into the sled. Most of these users had enough mobility and muscle control to get themselves into the sled. It can, on the other hand, be difficult for some to bend their knees because of their condition. This can make it difficult to use Spike with the current sitting position. Non-synchronized muscle control is also common, and this can affect the control of Spike. It is important to take non-synchronized muscle and/or body weight into account when developing a new version.

2.3.3 Amputation

An amputation is the surgical removal of an arm or leg. Around 80% of the people in Norway with an amputation have a lower limb amputation [20]. Depending on how the person is amputated assistive devices like Spike could be a good supplement for the prosthesis or wheelchair.

So far, Spike has been tested with several people with an amputee but only with single leg amputations. Generally, they handled Spike well, among other things because of the possibility for individual adjustment of the springs. This adjustment compensates for the uneven weight distribution of the body. The remaining question is how double amputees could adapt to Spike. It might be difficult to be seated properly in the knee sitting position with the current version of Spike. This is something to check out while developing the next version.

2.4 Paralympic sports

People that have shown interest in Spike are often already active within a sport. Sports like cross country sit-ski is directly impacted by a product like Spike since it is a further development of a sit-ski. Other activities like sled hockey, rowing and handcycling have also responded positively since they see Spike as a supplement to training for their main activity. This should be considered during development of a new version of Spike. The next sections describe some of the most popular Paralympic sports and how it could be important to take these into considerations in the product development.

2.4.1 Cross-country sit-ski

Cross-country sit-ski is an adaption of Nordic cross-country skiing. Paralympic cross-country skiing is one of the disciplines in the Winter Paralympic Games. The athletes use customized sleds that are mounted on standard skies (see figure 2.6). These sleds can have a range of different sitting positions and individual adaption. Spike is a natural improvement for using these sit-skies on bare ground. Feedback has indicated that Spike gives quite a similar movement pattern like skiing with cross-country skies.

Figure 2.6: An athlete skiing

2.4.2 Sled hockey

Sled hockey was invented in the early 1960s by a group of Swedes who, despite their physical disability, wanted to continue playing hockey. Sled hockey is basically the same as typical hockey but with different equipment. Players sit in a specially designed sled that is mounted on top of two hockey skate blades [21]. To keep balance, the sled is built with a low center of gravity which means that the legs are in front of the body, as shown in figure 2.7. Spike has received good response from sled hockey players, but an optimized product should have the same sitting position as the hockey sled.

Figure 2.7: An athelete playing sled hockey

2.4.3 Para-rowing

Para-Rowing is rowing or sculling open to both male and female rowers with a disability who meet the criteria set out in the Para-rowing Classification Regulations and Bye-Laws [22]. Para-rowing debuted in Paralympic in Beijing 2008. Like in sled hockey the rowers are seated with their legs in front of the body, as shown in figure 2.8. This activity requires a lot of upper body strength.

Figure 2.8: Birgit Skarstein competing in Para-rowing

Exero Technologies visited Boston Community Rowing in June 2017. Five of the para-rowers tested Spike and could confirm the synergy with rowing. Especially the use of core muscles were highlighted as one of the advantaged they saw in Spike. As in sled hockey, a more optimized version of Spike would have the same sitting position as in the boat.

2.4.4 Handcycling

Handcycling is becoming one of the world's fastest-growing disability sports and its recent inclusion into the Paralympic program further highlights its popularity [23]. Riders use specially designed bikes in either a kneeling, seated or recumbent (lying down) position and propel themselves using arm cranks, see figure 2.9.

Figure 2.9: An athlete handcycling

The first individual that received a prototype of Spike is primarily a hand-cyclist. He saw the potential for using Spike as complementary training beside the hand-cycling. For expanding the market share within hand-cyclists it would be beneficial to see how the new version could improve the physic for hand-cyclists.

2.5 Existing Solutions

Sports equipment for the disabled is a niche market with a mix of manufacturers and distributors. Assistive devices for exercise and sports accounted for 27 MNOK in Norway in 2014 [2]. The most common products suited for people with disabilities in the lower part of the body for exercise and sports are as followed:

- Handbikes (Figure 2.10B)
- Wheelchairs, with or without modifications (Figure 2.10D and 2.10F)
- Sit-skis, cross country and alpine (Figure 2.10A, 2.10C and 2.10E)

There are currently no similar solutions to Spike. The most comparable product is a ski sled with roller skis attached to the bottom, which is both unsafe and difficult to use (Figure 2.9A). Wheelchairs with a third wheel, where the user employs poles for speed, are somewhat similar (Figure 2.9D). Both solutions have disadvantages when it comes to steering and braking.

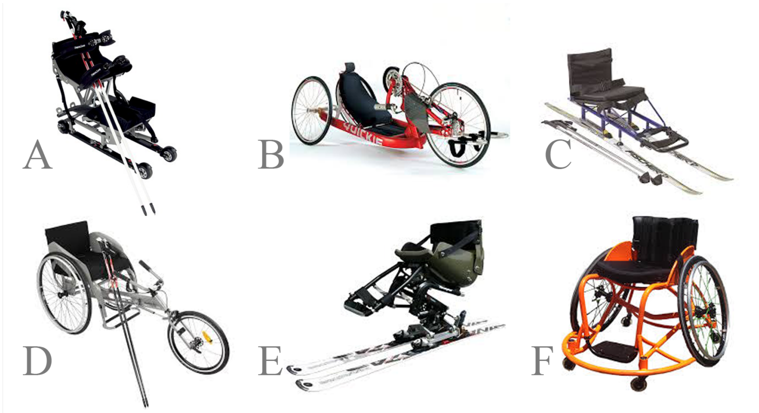


Figure 2.10: Different assistive devices

As shown in the figure 2.10, existing solutions have a lot of different sitting positions. Depending on the degree of disability and desire it is difficult to find one solution that covers all needs. By developing Spike further with a new sitting position, the product will become more attractive in the market and meet several needs.

Exero Technologies has made a competitor analysis for Spike which could be reviewed in Appendix **??**, 3.0 Competitors.

Chapter 3

Method

3.1 Literature acquisition

To find answers to the research questions relevant articles were reviewed. The research was done by using search engines like “Google Scholar” and “ResearchGate” searching for “Assistive technology,” “Prototyping,” ”Paralympic sports,” and “Design Theory and Methodology.” Articles provided by Christer Westum Elverum (Lecturer at the Department of Mechanical and Industrial Engineering) was also used to find theory on this subject. The methodologies and categories most interesting for the master thesis were chosen to conduct the product development.

3.2 Product development method

To decide which product development method to use during the master's project, the author's previous experience and the gathered theory was considered. The product development method has to fit how Exero Technologies is organized today. As a small start-up company, there are limited resources available, which is important to take into consideration. From the theory, there were two main principles presented, classic and agile product development. These two principles represent quite different approaches to product development. To find out which method to use for the master thesis a list of pros and cons were made.

3.3 User profile

A user profile is an example of a potential user. This profile will help the authors to develop a product that will satisfy specific needs. Exero Technologies has established a broad network of athletes with a range of different disabilities. In this project thesis one profile will be presented, [redacted]. [redacted] contacted Exero Technologies in September 2017 and requested a version of Spike which was customized for him.

As [redacted] is important to the prototype process presented later in this chapter, the user profile is presented bellow.

3.3.1 Test subject

Born: [redacted]
Hometown: [redacted]
Activity level: Former Paralympic athlete

[redacted] is paralyzed from the waist down and use a wheelchair to move around. He is used to a high activity level and has participated in a Paralympic game in the sport of cross country sit-skiing. In the Paralympic game of [redacted], he got three podium finishes. Today he is active with various types of activities, such as strength training, sit-ski, and hand-biking. Because of several surgeries, he cannot bend his knees, and therefore can not use Spike as it is today. Instead, he has a sit-ski similar to the one seen in figure 3.1, which he has used the last 20 years. For him is it important to have reliable equipment which is safe and easy to adjust to different activities.

3.4 Prototyping

At the beginning of September, Exero Technologies was contacted by [redacted]. [redacted] had learned about Spike during its development and was curious if it would work with his disability. As mentioned earlier, [redacted] is paralyzed and because of a previous surgery, unable to bend his knees. As Spike requires bent knees to get in the correct position, it was quickly decided as unfavorable for [redacted]. At this time Exero had already planned to develop a product with another sitting position. However, as the new product was scheduled to be finished as late as June 2018, it would be a long wait for [redacted]. [redacted] was eager to work with Exero, so it was instead decided to use [redacted] as a test subject for the new sitting position. Exero had at this time no knowledge if it would be possible to use the steering system while positioned differently. Such prototype had the potential to give valuable insight early on in the product development process. A total of three prototypes were made during this project, all with the overall purpose of learning how the steering system functions combined with another sitting position. To ease the prototype process, it was decided to connect Exeros existing steering system with an already existing sled. This was seen as the simplest way of testing the concept and therefore in compliance with the methodology of Ulrich and Eppinger [1]. To make this possible, Exero were allowed to borrow [redacted] old sled for several weeks. The sled was an older version made by the company HandiNor (see figure 3.1). A problem with this solution is the tilting of the steering system during turns. This tilt decreases the distance between the wheels and the sled frame which might lead to contact bewteen the two parts. This problem had to be solved during the prototype process.

One of the prototypes were analytical while the two others were physical. The prototyping process followed Ulrich and Eppinger's four steps for planning the prototype [1]. The positions of each prototype according to the Focused/Comprehensive and Physical/analytical dimensions can be seen in figure 3.2. The process of each prototype will be further presented below.

Figure 3.1: Handinor cross-country sit ski sled

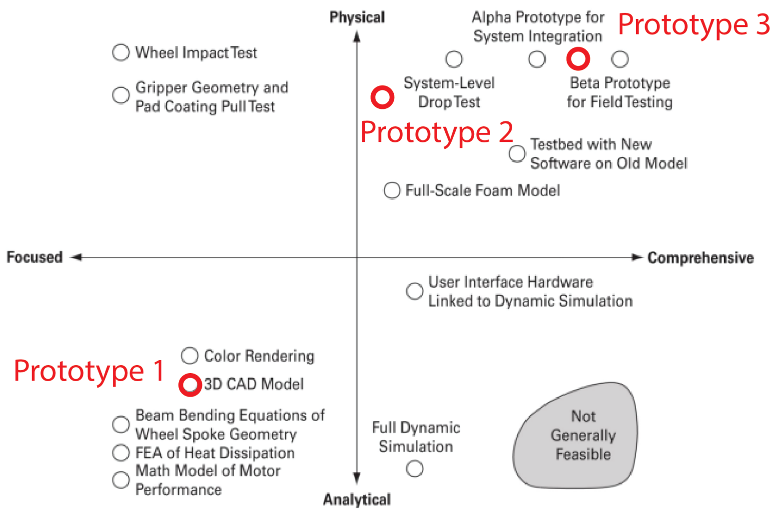


Figure 3.2: The three prototypes according to their respective dimensions [1]

3.4.1 Prototype 1

Planning the prototype

The first prototype had the following purpose:

- To explore and visualize a chosen solution for connecting the steering system and the original sled could be connected.
- Ensuring that chosen connection would not interfere with the movement of the wheels

It was decided that the first prototype was going to be analytical. The reason was that analytical prototypes tend to save both time and money compared to physical ones [1]. Ulrich and Eppinger suggest that analytical prototypes tend to be more flexible than physical prototypes. As a flexible design would make it easier to make changes to the chosen solutions at a later stage, an analytical prototype was preferable. The prototype would be focused, mainly considering the connection between the steering system and the sled. There were also decided not to attempt to approximate the final product. This means that any “shortcuts” possible without influencing the purpose of the prototype would be performed.

Experimental plan:

1. Brain storm different solutions
2. Pick a solution for further work
3. Model the chosen solution in 3D
4. Check if solution work as intended
5. Check visually for wheel collision

The prototype process was planned to begin on September 4th. Brainstorming and deciding on a solution were planned to take two days. The modeling of the chosen prototype was planned to take two days. An additional three days were given to evaluate the prototype and gather knowledge. The whole experiment was planned to be finished on September 9th.

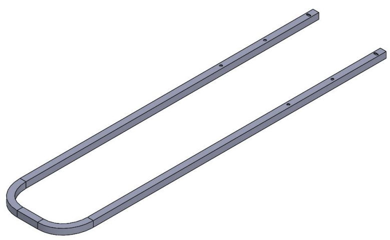
Execution of the prototype process

Several possible solutions were sketched during a brainstorming session between the authors. The sketches were further discussed, and especially four criteria were crucial for deciding which solution to continue working on. Based on the criteria one of the solutions were chosen and modeled in 3D. The criteria are presented in prioritized order bellow:

- **Assumed cost:** The project had a limited budget, and it was important to find a cheap solution
- **Height from the ground:** From previous research, it was concluded that the height from the ground has a large effect on stability and safety of the sled [24]. There is also a requirement of max height within cross country sit-ski competitions, with 40 cm from the ground to the athletes hip [25].
- **Minimum complexity:** The purpose of the prototype was to test a concept. It was seen as beneficial to achieve minimum complexity
- **Adjustability:** This is an essential aspect of the finished product. Examples of adjustable variables are length, height, angle of seating etc. For testing the concept on this prototype, however, it was seen as a luxury

The chosen solution scored high on all criteria except adjustability. It quickly became clear that adjustability and height were hard to combine. The adjustable solutions demanded more space which pushed the sled higher from the ground. As adjustability had a low priority sketches focusing on this were quickly rejected to instead focus on the height from the ground. After a solution was chosen, the evaluation of the other solutions was kept as a ”truth-document” in case of changes made later (see section 2.1.3 Set-Based Design).

Before beginning the modeling process, existing models were gathered to examine what could be reused. Exero already had an older model of the steering system, as seen in figure 3.3b. This model was used with some modifications. There was, however, no existing model of the sled. To save time, only the base-frame of the sled was modeled (see figure 3.3a). This was made possible by taking measurements of the actual sled borrowed from [redacted]. It was assumed that this frame was the part of the sled that was most in danger of hitting the wheel during a turn.



(a) 3D-model of the base frame of [redacted]' old sled

(b) 3D-model of the original steering system

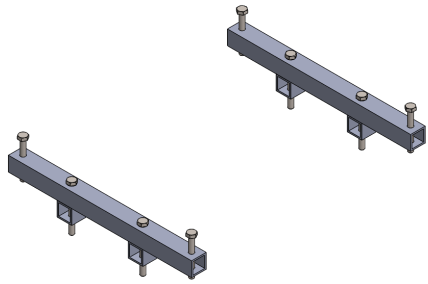
Figure 3.3: Figure showing the sled frame and the steering system

Both the original sled and the old steering system were mostly made of square tubes. To ease the production and alignment of the two systems, it was decided to decrease the dimensions of the original steering system from 25mm x 25mm to a slimmer 20mm x 20mm equal to that of the sled frame. It was also decided to shorten the new steering system by 60 mm compared to the existing one.

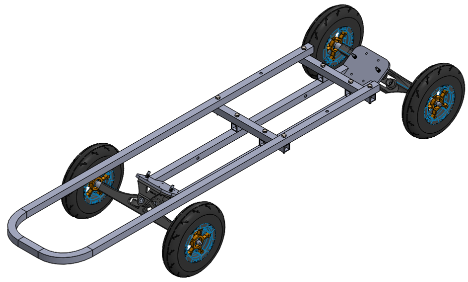
Previous research done by Exero had shown that a shorter distance between the axles provided a more responsive steering system with a decrease in turning radius. On the original Exero sled, the change of this distance is limited due to the positioning of the feet and knees in the original sitting position. Touching the wheels is especially dangerous for paralyzed users as they would not recognize any feeling of pain which might lead to grave injury. The new sitting position provided more flexibility regarding the earlier mentioned distance. Though trying out a shorter system were not seen as the purpose of the prototype, it was decided that it would not interfere with the original purpose.

To ensure sufficient distance between sled frame and wheel during turning the model were inspected visually with a 14° angle in the steering system. From earlier research, it was concluded that 14° was the steering systems maximum angle when performing sharp turns [24].

The chosen connection can be seen in figure 3.4a. It consisted of a simple assembly of two crossbeams made of 20mm x 20mm beam supported by four smaller 20mm x 20mm squares. The whole assembly with sled frame and steering system can be seen in figure 3.4b.



(a) 3D-model of chosen connection



(b) 3D-model of the assembled prototype 1

Figure 3.4: Figure showing both the connection alone as well as connecting the sled and steering system

3.4.2 Prototype 2

Planning the prototype

The second prototype had the following purpose:

- Validating the non-wheel-collision of the chosen connection form testing with prototype 1
- Short term testing of the steering system chosen in prototype 1

The second prototype was planned as a simple physical prototype. The transition from analytical to physical was decided to be done because of the possibilities of a physical prototype. There is some aspect that just is not feasible to explore by analytical prototypes alone [1]. As the purpose of this prototype was to get a first-hand experience of how the steering system would work in a different sitting position, the transition to physical prototype was a natural choice. Now more of the overall functionality would be tested. As of this, the prototype could be seen as more comprehensive compared to the first prototype even though the main focus still were on the connection alone. Prototype 2 was viewed as more or less a transition prototype between the first and the third prototype. Therefore it was decided to minimize the development cost and time as much as possible.

Experimental plan:

1. Explore available materials
2. Build a simple physical prototype that resembles prototype 1
3. Validate the results from prototype 1 (non-wheel-collision etc.)
4. Validate that the steering system works with the new sitting position

Prototype 2 was planned to begin shortly after finishing the first one. The project was intended to start the day after ending the first prototype process, on September 10th. The building was expected to take four days, and the testing would be performed quickly with the use of one single day. The project was scheduled to be finished on September 14h.

Execution of the prototype process

The prototype was simply made by trying to connect the sled and the steering system in the easiest and cheapest way possible. Exero had at this time access to a supply of wooden scrap materials. It was therefore decided that a connection should be built by connection the sled and an old steering system by only using the available material (see figure 3.5). Wooden plates were stacked upon each other until it reached a height equal to the one tested in prototype 1. Different heights were also examined to discover the absolute lowest connection height that was possible. This set-up also enabled short-term testing with the steering system.

Figure 3.5: Prototype 2 assembled

3.4.3 Prototype 3

Planning the prototype

The third prototype had the following purpose:

- Long term testing of the steering system chosen in prototype 1
- Long term testing of the performance with an actual user
- User feedback on the functionality of the steering system with a passive sitting position

The final prototype planned for this pre-master project was also decided to be built as a physical prototype. A physical prototype was a natural choice considering the purposes of this prototype. To achieve this purpose, it was also seen as necessary to create a comprehensive prototype.

Unlike the other prototypes, the connection between the sled and the steering system were no longer the main focus. Now the system as a whole was seen as equally important to fulfill the prototype's purpose.

Experimental plan:

1. Make adjustments to prototype 1 according to result from prototype 2
2. Use the new 3D-model to make mechanical drawings for production purposes.
3. Manufacture the parts necessary for the prototype
4. Assemble the prototype
5. Perform simple test-runs with the team members
6. Perform test-runs with [redacted] for a first-hand experience and deliver the prototype to him for long-term testing
7. Follow up [redacted]' experience with interviews and surveys

The work with implementing the knowledge gathered from prototype 2 into the 3D-model was scheduled to begin on September 25th. Three days later on September 18th, the necessary adjustments should have been made and the drawings delivered at a local workshop in Trondheim. It was estimated that the production would take approximately three weeks, with an expected delivery at October 16th. The assembly would be performed by the authors and was expected to take two days. As a summary, the building of the prototype would begin at September 18th and end on October 18th. Testing the prototype with [redacted] was planned to continue past this pre-master and further into the master thesis.

Executing the prototype process

The third and last prototype was developed by using the 3D-model from the first prototype with some adjustments learned from the second prototypes. When satisfied, this model was used to create mechanical drawings. The drawings were sent to a mechanical workshop in Trondheim called Ula Jern. This workshop was familiar to Exero and trusted for delivering high quality. There were, however, some misunderstandings considering the schedule for production. The authors had not taken the fall holiday season into account during planning. At September 9th Ula Jern shut down for a week, which led to a delay in the delivery. As this was the last prototype to be built during this project, it did not affect further projects. Still, it left limited time to test the prototype before the winter season would set in.

Ulrich and Eppinger suggest testing prototype with conventional experimental methods to maximize the value of the prototype [1]. However, the feedback wanted from testing this prototype is quite complex as it has more to do with feeling and experience. However to be able to make the results somewhat comparable a survey with answers on a scale from 1 to 10 were used. This makes it easier to compare this prototype with others made later in the master's project. It also makes the data easier recognizable for later reviews. However, it is important to emphasize that the survey is a supplement and not a replacement for the written notes from interviews made with the users.

The prototype were tested both on delivery day together with the authors and by the [redacted] alone on later occasions. A written contract was signed by both parties when the prototype was handed over for long-term testing. The contract was made to ensure a common understanding and reduce the legal risk of Exero Technologies and the authors. The contract can be seen in Appendix **??**. The finished prototype can be seen in figure 3.6.

Figure 3.6: Prototype 3

3.5 Product requirements

g When creating product requirements specifications, it is important to have some guidelines. The specification will make it easy to follow and give an analytic approach to the product requirements. To do so, the authors created a table inspired by the Kano-model [26]. The table is divided into four categories; basic need, performance need, delighters and at last a comment on the aspect. A ”basic need” has to be fulfilled to not disappoint the customer or user. ”Performance needs” will lead to more satisfaction the more the product fulfill the requirement. ”Delighters” can be seen as a bonus, something the customer does not expect but that will increase satisfaction.

In order to find the requirements the authors conducted a workshop. During this workshop, previous experience from working with Spike was considered in addition to findings in this project thesis. After finding the requirements, they were sorted and specified in a table.

Chapter 4

Results

4.1 Product development method

To decide between classic and agile product development method a list of pros and cons was conducted. These pros and cons were chosen according to how it would fit Exero Technologies. Factors that need to be considered is among other; time, resources available and previous experience.

4.1.1 Classic Product Development

Pros:

- The authors have experience with IPM Model (Stage Gate) from their bachelor thesis
- Divided into defined phases with sub-goals which make it easy to measure progress
- Reduce resources in the early stages of development

Cons:

- Reduce flexibility along the process
- Costly to make changes late in the process
- Strict setup reduce creativity

4.1.2 Agile Product Development

Pros:

- Keep flexibility along the process
- Postponing decisions leads to more information gathered along the project that can be taken into account
- Agility is an important advantage for a start-up company

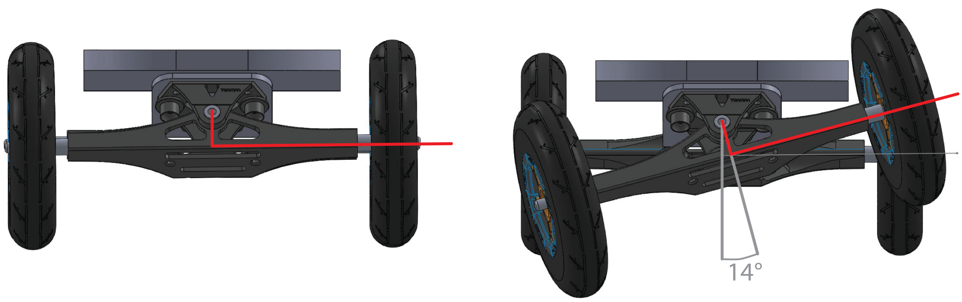
Cons:

- Demand more resources early in the process
- The authors have less experience with these type of methods
- Seen as a more demanding process compared to classic product development [15]

4.2 Prototyping

4.2.1 Prototype 1

The visual inspection of the steering system showed a sufficient distance between the sled frame and the wheels (see figure 4.1).



(a) 0° tilt

(b) 14° tilt

Figure 4.1: Front side of the steering system with 0° and 14° tilt

4.2.2 Prototype 2

The second prototype validated the choices made in the first one. The prototype could easily turn, and the sled frame did not collide with the wheels when turning at maximum tilt.

Short-term testing showed that the sled could be mounted even lower than the results from prototype 1. The reason was that the steering system never tilted as much as assumed. As the height already was satisfactory, the extra distance was not corrected but used as a safety factor.

4.2.3 Prototype 3

The prototype was fully assembled on October 26th and was tested the same day. [redacted] was, during the inspection, satisfied with the adjustments and eager to try it out. The first half hour was used for adjusting the springs and brakes. [redacted] felt a constant improvement by each adjustment, but did not feel comfortable in the sitting position. This influenced his impression, but overall he was satisfied with the solution. He managed to handle the sled, and he felt secure while doing so. The next step was to hand the prototype over to [redacted] for further long-term testing.

At December 8th, [redacted] was interviewed to give feedback from the last couple of months. He did in total have three sessions with the prototype before the weather made him switch to cross-country skies. [redacted] was in general very satisfied with the prototype. He informed that it could not be compared to his previous sled and was to consider as a new dimension both in performance, comfort, and safety. At this interview, he admitted that it did not go as well (as he expressed) during testing of the prototype in Trondheim. At the previous test, he felt that he could not find the right sitting position that he was used to. The next day he went to the local Welfare Service in [redacted], and they discovered that he did not have the proper seat adjustments. After this adjustment, which he pointed out was a problem with the ski sled, the prototype had been working perfectly. He was satisfied with the prototype, except the sitting position and seating. This can also be seen in the survey answered by [redacted] were ”seating comfort” was answered with a low value (see table 4.1). He informed that he was looking forward to experimenting with this further into the master’s project. [redacted] concluded the interview by expressing that he would gladly test out further prototypes and adjustments. The full interview can be seen in appendix **??**.

Table 4.1: Survey answered by [redacted]

Survey										
Question	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1. Rate the prototype’s ability to turn								x		
2. Rate how easy prototype is to use									x	
3. Rate how safe you feel in the prototype									x	
4. Rate the prototype’s functionality against competing products										x
5. Rate the prototype’s functionality in traffic									x	
6. Rate the prototype’s functionality on country roads									x	
7. Rate the functionality of the braking system										x
8. Rate the seating comfort					x					
9. Rate the fastening system									x	
10. Rate the adjustability									x	

4.3 Product requirements

In this section, the product requirements will be presented. This will be a summary of requirements mentioned in previous chapters and what the authors have experienced from testing Spike. In addition, to be a functional product, it is also important that the new version of Spike fits the vision and goal of Exero Technologies. Branding, design and sales channels must also be considered to make a product that can be commercialized. The product requirements must align with how Exero Technologies plans to stand out in the market.

The next bullet points present some of the areas where Exero Technologies has the opportunity to create a competitive advantage in the market.

- Emphasize design, from the product itself to the marketing. People with disabilities have the same demands to design as others. How the product make you feel is also an important factor.
- Emphasize independence and erase differences between people with and without disabilities. Exero Technologies wants to create products the user can manage on their own.
- Experiment with new manufacturing methods to create customized solutions at a lower cost, e.g. additive manufacturing. Assistive devices are often made in small series which increase the cost when using conventional manufacturing, e.g. molding, milling, and extrusion.

The following table 4.2 shows the resulting product demand specification:

Table 4.2: Product demand specification

Product demand spesification				
Aspects:	**Basic need**	**Performance need (values)**	**Delighters**	**Comments**
Handbrake	x			This is a demand from the customer (The Norwegian Welfare Service)
Able to compensate for uneven bodycontrol	x			For people with uneven muscle control or limb loss
Adjustable seat	x			Easy to adjust from user to user
Adjustable fastening mechanisms	x			To fit different kinds of disabilities
Flag mount	x			This is a demand from the customer (The Norwegian Welfare Service)
Fenders	x			To prevent splashing and clothes getting stuck in the wheels
Prevent tilting	x			To reduce the chance for accidents and injuries
Easy to use	x			Needs to be easy to understand how to use and maintenance
No sharp edges	x			To prevent injuries
Hidden moving parts	x			All moving part should be covered to prevent injury
Easy to customize			x	In order to get a personalized setup and for making it possible for several people to use the same sled
Easy to transport			x	Fit in the storage compartment of a regular
Water bottle holder			x	
Maintenance		$<$4 hours per year		Easy to clean, few tools needed for adjustment
Weight		$<$10 kg		To make it possible for less trained people to perform and to stay competitive with competitors
Cost		$<$35 000 NOK		Cost of production needs to stay below this in order to make profits
Turn radius		$<$5 m		Make it able to turn 180 degrees on a regular road
Height		$<$40 cm		Measured from the user's waist and down to the ground. The same as regulations for sit-skis.
Carrying capacity		$>$120 kg		

Chapter 5

Discussion

It is, based on the results, difficult to choose a single method to continue with in the master's project. All the methodologies have both pros and cons, and a type of mix or hybrid could be the best option. As the authors have previous experience with the IPM model from the bachelor thesis, this might be a tempting solution. With this type of model, it might be easier to follow each stage in the process. It could also reduce resources, which is crucial to consider in a small start-up. Such process can, on the other hand, reduce creativity, as several decisions need to be made relatively early in the process. This is where agile product development or set-based design have their strengths. It would be a benefit using a flexible process so that changes can be made late without huge expenses. For a start-up company, the real downside with such agile methodology are resources needed at the start of the development process. Both classic and agile product development could be a good fit for the master thesis. One argument that would support agile product development is the fact that Exero Technologies is a start-up with agile characteristics. Unlike several competitors, Exero Technologies can use this agility to respond quickly to market changes. This might be worth the extra costs at the beginning of each development process. Exero Technologies need to keep this advantage as long as possible to gain new market shares. To survive the company needs to do something different than the more established competitors with much more experience and already existing market shares.

Prototyping was also considered as a tool to perform product development. Prototyping can be used as a tool regardless of classic or agile product development is chosen. Since none of the team members in Exero Technologies have a disability, it is important to have a user-oriented product development. Exero Technologies see this as one of their biggest advantages compared to the most competitors who are large companies. Both analytical and physical prototypes would be a resource for Exero Technologies. By doing analytical prototypes first, Exero Technologies may reduce some of the costs associated with outsourcing the building of physical prototypes. Exero Technologies also have access to several 3D-printers which could be used for rapid prototyping. The engineers at Exero Technologies have experimented with 3D-printing the fall of 2017, and it could be valuable to take advantage of this resource during the master's project.

The research of other products in the market showed a large variety of equipment with quite different sitting positions. This, as well as the different activities the equipment represent, should be considered when continuing the work in the master's project. Focusing on this might make the adaptation of the new product easier for new athletes.

The prototyping method used during this project can be described as a point-based approach. The decision of using such approach can be justified by the purpose of the prototypes. The purpose was simply to answer a ”yes” or ”no” question, namely ”will the steering system work in another sitting position.” To answer this question, a point-based approach is sufficient. It should, however, be considered to use a set-based approach in the master thesis, as it will be important to extract knowledge on optimization from each prototype.

The last prototype in this project was made by the professional workshop Ula Jern. There was, however, an alternative to building the prototype ourselves in the mechanical workshop at NTNU. Even though the authors had some experience with metalworking, their skill was considered unsatisfactory for this prototype. The purpose of the prototype was to perform long-term testing by an actual user. Long-term testing in this case also includes solo testing by the user outside of safe clinical lab environments. It was decided to focus on making the prototype at the highest possible quality and therefore use a third-party workshop.

The authors has that the handicap-community in Norway is a very positive and excited community. Even though this makes it a motivating and rewarding community to work with, it can create some complications when receiving feedback. Exero has experienced that some feedback might be rated more positive than reality. This should be taken into consideration when reviewing such results. The fact that many of the products on the market today is poorly made might also make it easy to impress the users with thought out solutions. This does, however, not mean that the solutions are good enough and has no room for improvement. It is therefore beneficial to review different feedback from the same person relatively to each other and view them as an input on the direction of the development process instead of the actual value of the product.

From the survey answered by [redacted], it is clear that the sitting position is the worst aspect of the prototype. The question considering comfort has a much lower value compared to the others. These results, as well as the direct feedback from [redacted], might indicate a need for a greater focus on comfort during further development.

Based on previous experience and new knowledge from the project thesis, the product requirements for the new version was established. These requirements are not complete, and there is a high probability of changes during the master thesis. Exero Technologies has experienced several sudden changes because of new information or new knowledge along the way.

Chapter 6

Conclusion

During the project, several activities and different solutions have been reviewed, and should be considered during the development of the new version of Spike. It should be considered to use a sitting position already known from other activities.

The product demand specification developed during this project will be used as a guide during the product development process in the master's project. It is, however, acceptable that changes might occur to this specification at a later date.

The authors have decided that it should be experimented with an agile product development method during the master project. It will be focused on set-based thinking both in development and during prototype processes.

The results from testing with [redacted] has showed that Exero's steering system also function as intended in other sitting positions. This conclusion encourages continued work toward a new version of Spike compatible for people not able to sit on their knees.

Further work:
To develop and test new sitting positions during the master project, more potential users should be contacted. NTNU SIAT could assist as they are known in the community. The authors should continue communication with [redacted] to retrieve information from both the old and future prototypes.

The Norwegian Welfare service should be contacted to learn more about direct requirements for products and production.

Based on the feedback from [redacted] it was concluded that the steering system worked as intended. [redacted] was however not satisfied with the sitting position of the old sled. The sitting position should, therefore, be the main focus for further work. The master's project should also focus more on the details of a new product as the main concept is concluded as successful. It should be looked into the use of different materials and look for inspiration in other products.

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Appendix B

Test reports

Table of contents

B-1 - In-house testing

Wheel count, wheelbase and axle length

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 15.02.2018

Summary:

In this test were the authors testing how different wheel counts, wheelbases and axle lengths would affect the steering and balance of Spike. Initially was this planned to be conducted with a test user but canceled in the day before. The in-house test was conducted at Leangen Icehall in Trondheim the February 15 and followed up 8 March at NTNU Gløshaugen. Three wheels were quickly rejected as a good solution, mainly because of poor balance and reduced turning radius. A small truck at the back was an improvement of turning radius, but the small wheels made it difficult to handle. It might be interesting to test out this further with new wheels. A larger axle length in the front made the sled more stable but too wide will come into conflict with the ski poles. This is also something that should be tested out further.

Preparation and planning:

The wheel count, wheelbase and axle length prototypes, were initially planned to be tested directly with a user with no prior in-house testing. At the day of testing, however, the user canceled due to a sudden illness. Instead of canceling the test it was decided to perform an in-house test instead. It was decided to test out three setups A,B, and C (explained below). Questions that the authors wanted to answer were among others: How would three wheels work instead of four? How could different lengths between the axles affect the steering? Could a small truck back make a difference? Tools and necessary equipment were brought along to the test site.

Purpose of the test:

- Test how different setups affect the steering responses
- Measure turning radius with each setup

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**
Test setup A*	Didn't affect the turning radius. More stable than regular truck in the front. Could come in conflict with ski poles.	Had a good feeling using this. A bit smaller could help with using the poles without getting in conflict.
Test setup B*	Better turning radius. Less stable. Skateboard wheels are too small.	Could be interesting to test with larger wheels. Could be possible to reduce distance between the two axles.
Test setup C *	Bad effect on the turning radius. Poor balance, difficult to handle.	This needs a huge improvement to work. This is rejected as of now.

*Setup A= Regular channel truck in the rear and the maximum axle length in the front.

*Setup B= Small skateboard truck in the rear and the maximum axle length in the front.

*Setup C= One wheel in the rear and the maximum axle length in the front.

Results:

During the initial testing at Leangen Setup A indicated that a wider truck in the front considerably increased the stability of the sled. The authors experienced that it was significantly more difficult to tip over with this feature. Setup B showed to be considerably less stable compared to Setup A. As they both had the same axle length in the front it was clear that the issue was due to the smaller skateboard truck in the rear. Setup B made the sled unstable which made it difficult to keep the sled in a straight line. The smaller wheels of the skateboard truck also further decreased the stability of the sled.

The first initial test indicated that a standard truck back and an increased axle length in the front made the sled more stable. It was significantly more difficult to tip over with this feature. Besides, showed the second test that it does not affect the turning radius. However, did it get in conflict with the poles at some times and this has to be investigated later.

The first initial test indicated that a small truck back and an increased axle length in the front made the sled less stable than a standard truck. It was difficult to keep the sled in a straight line, something that is not easier with the small wheels. The turning radius where decreased, but it was more difficult to lean the weight over and keep the balance. The benefit with a smaller truck at the back is the possibility to move the truck beneath the person and thereby decrease the length between the front and back truck. This will make the turning radius smaller.

The first initial test indicated that one wheel back and increased axle length in the front was very unstable. The authors struggled to keep control, especially at higher speeds. The turning radius was also significantly increased when testing at the parking lot. The benefits of the solution is a simpler (cheaper) solution with lower weight. However was the downside considered to be much bigger and the solution needs improvements to be relevant.

On March 8 the authors took the Spike prototype with different setups outdoors to measure turning radius. One of the authors were chosen to observe and measure while the other operated the Spike prototype. Keeping the same test pilot on each measurement contributed to the repeatability of the testing procedure and to make the results comparable. The test location was in a parking lot were each setup assembled, mounted and the turning radius measured.

The following table show an estimate of the turning radius based on several rounds of measuring the turning radius. Different adjustments on the spring will affect the turning radius, and it was tried to keep it the same adjustments in every test.

Setup	**Turning radius in meter**
Test setup A*	Approx. 7m
Test setup B*	Approx. 5,8m
Test setup C *	Approx. 11m

Discussion:

A real end-user should also conduct this test, but it seems straightforward that setup C is not an improvement. Getting feedback on the two other setups could be interesting. The test site could also be better since the Icehall at Leangen have limited space and could have affected the feeling. Setup A is probably the easiest to implement in the final solution, but maybe not in the first version. Both of the authors focused on turning radius and balance when testing the different setups, which could be less of what they should have tried out.

Conclusion:

Setup A is considered to be an improvement from the current solution but needs to be made to not letting the ski poles get in conflict with the wheels. Setup B is also an improvement but will require more work to implement. This will be worked further with at a later stage. Setup C did not work as intended. This will not be worked further with as of now. Needs a game-changing improvement to be considered.

B-2 - In-house testing

Truck angle adjustment

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 10.03.2018

Summary:

In this test were the authors testing how different truck angles would affect the steering of Spike. The in-house test was conducted at NTNU Gløshaugen on 8 March. The prototype used in this was a set-based prototype which made it possible to adjust quickly during the test session. It was decided to start with the largest tilt, 70 degrees, and thereby reduce it down to 30 degrees. As expected did 35-45 degrees measured to give the best turning radius. From several sources online have the authors found out that 35-degree truck angle commonly used. Since the in-house test confirmed a good result with 35 degrees is this decided to continue to use. This is also something that could be tested out further.

Preparation and planning:

The prototype of trucker angle adjustment, where decided to be tested in-house by the authors. As mentioned earlier was it unclear which angle of the trucks that was considered most optimal. The prototype was made as a set-based prototype which made it possible to make several adjustments during one test session. It was decided to do the test nearby NTNU Gløshaugen on a suitable parking lot. The prototype was delayed which resulted in a more demanding condition outside with snow and ice in the parking lot.

Purpose of the test:

- Test how different angles affect the steering responses
- Decide an optimal truck angle

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**

Test angles from 30 - 70 degrees	See table below	Difficult to keep exact same momentum in each run
Decide an optimal truck angle	35-45 degrees seems to be best	Since 35 degrees are commonly used in mountainboarding this will be used further.

Results:

The results confirmed what the authors indicated, which where an optimal angle of the trucks tilted 35 degrees and 45 degrees. The prototype worked as intended and made it possible to make a data set, which characterizes set-based prototyping.

The following table show an estimate of the turning radius based on several rounds of measuring the turning radius. Different adjustments on the spring will affect the turning radius, and it was tried to keep it the same adjustments in every test.

Degree of tilt	Turning radius (meters)
70 degrees	12m
60 degrees	9m
50 degrees	7m
45 degrees	6m
35 degrees	6m
30 degrees	8m

Discussion:

By having a set-based prototype the time used to test each setup was relatively short. However, did the authors notice a drawback with the prototype. For each adjustment, the test person had to go off the sled. This could be a potential problem when testing with a disabled person, where the transaction from wheelchair to sled multiple times would be demanding for the test subject. It is difficult to say if the tests were the same every time. Even though one person was used during the test, it was difficult to keep the same position every time. This uncertainty was tried to avoid by doing the same test three times each and then make an average estimate. Snow and ice in the parking lot might have affected the result, despite that the test person tried to keep the movement the same each time.

Conclusion:

As expected were 35-45 degrees the most optimal regarding turning radius. According to different articles online it seems reasonable to have 35 degrees when using mountainboards. This was also experienced as one of the best adjustments from this test. As of now the first version of Spike will continue with 35 degrees tilt until it has been tested out further. There was no obvious reason for changing that in the nearest future.

B-3 - Long-term user-testing

Test subject 1

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 15.05.2018

Summary:

This was the first person that has tried Spike over a more extended period of time. This has lead to much information which has contributed to both product development and business. The test subject has shown great interest from the beginning and used the Spike in test session, events and home in his natural environment. This process has been resource-demanding from the authors' point of view that has made a new prototype to give this test subject. In addition, have his use of Spike also led to maintenance and customization. This has given the authors a lot of knowledge and experience which have been difficult to achieve otherwise. The authors have been able to do observations, workshops, event testing and “thinking aloud” with this test subject. In general are the authors positive with this type of testing because of the value it gives in both product development and business. This type of testing is concluded to be something to continue with.

Preparation and planning:

Test subject 1 was introduced to Exero Technologies through the first person that tested the prototype during the authors' bachelors' project. In April 2017 the first test with subject 1 occurred. The location for the testing was Trondheim Spektrum, and it was quickly discovered that the test subject had extraordinary physical strength and endurance. After several tests the following months the subject presented his wishes to either buy or borrow a version of the Spike prototype. Exero saw this as an excellent opportunity to get more feedback and therefore built an additional prototype for the test subject. Since the fall of 2017, the subject has been using this prototype regularly whenever the weather condition would allow for it. Most of the preparation has been getting in contact with the test subject and plan different test that has been interesting to check out.

Purpose of the test:

- To see how Spike would work during a longer period of testing

- Test how Spike will work outside the direct use, how to transport, store and maintenance etc.

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	Result:	Comments:
Initial test with Exero Technologies present	Went very well, test subject have clearly control over the sled.	Test subject is eager to test out more!
Test subject test alone home	Test subject have done approximately 7 session by himself at home	A lot of good feedback from testing. Place for water bottle and flag needs to be implemented
Follow up meetings and feedback	Test subject have attended several workshops and test sessions	Test subject is often “too” positive. Need to take his answers carefully

Results:

After the delivery of the prototype, several tests and conversations were conducted between the authors and the subject. The subjects access to its own prototype created a constant stream of feedback regarding problems as they were discovered. This feedback allowed for quick responses in the development process. The communication mainly occurred either by phone or chat. Especially the chat option seemed to lower the threshold for the amount of contact the subject would initiate. This added to the amount and how often feedback was given from the subject. During the testing period, the subject also began making its own adjustments to the prototype. Adjustments like mounting a water bottle holder and mounting on a reflective pennant. As the subject went through the trouble of making these adjustments, it views as features required by the user. These types of features were valuable as they were not previously thought of by the development team. The ideas for such features had a clear origin in the subjects ability to use the prototype in the subjects' natural environment. In the early spring of 2018, the authors also visited subject 1 to inspect and perform changes to the prototype.

Discussion:

To have the possibility to make changes and get more feedback from the same person have been convenient for the authors. Having a long-term test user has also been more demanding in resources like time and money. It is expected that the authors do maintenance beyond regular washing and adjustments. Although this is resource-demanding has it also revealed new problems and features that were not intended before the long-term test started. Most of the knowledge has come from conversations and observations during this period. It has been some difficulties in the communication between the authors and the test subject. Several times have the authors been unable to get in contact with him, and he has canceled several times. He often gives positive answers without having the necessary information to give this. The authors have learned to take his statements carefully, but still professional.

Conclusion:

The value of having a lead user like test subject 1 has been priceless. He has tested the sled out a lot and given the authors a challenge during the period. This has uncovered some of the challenges that could occur when using the product in the intended environment. By having a lead user have the customer, “NAV Hjelpemiddelsentralen” showed more interested along with other stakeholders. Even though is the resource-demand in this method considered to be worth doing when developing a hardware product.

B-4 - Long-term user-testing

Test subject 2

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 20.05.2018

Summary:

The test period with test subject 2 has been quite similar to test subject 1. This case has proven that most of the experience from testing with test subject 1 also is related to others. In this case has observations, workshops, event testing and “thinking aloud” been conducted. It has been easy to keep in touch and communicate with the test subject, and the test subject has shown great interest in the development process. Spear has been a rougher and less complex prototype than Spike. In general is the prototype consider successful and it seems to be possible to commercialize this product at a later stage. The most critical part of Spear is considered to be the seating and the sitting position.

Preparation and planning:

In August 2017, Test subject 2 made the initiative to contact Exero Technologies through their Facebook-page. He had heard about the company and Spike through test subject 1. Test subject 2 was the first athlete in contact with Exero, not able to use a sled with a knee-sitting position. At the time of contact, Exero already had plans of making a version of Spike with a different sitting position in the future. As the subject was eager to try a new concept, the plans were pushed forward, and a simple prototype was created during the pre-masters' project.

Purpose of the test:

- To see if Spike could be further developed into a sled with a different sitting position (Spear)
- Retrieve feedback on important aspects to consider with the new version over a longer period of time

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**
Build a prototype of Spear	Build an add-on to the test subjects sit-ski	This went as planned and seems to work as intended
Test out Spear with test subject 2	Test subject did manage the sled after a half hour with adjustments	The pillow seems to be a critical part of this prototype
Get feedback from a longer period of testing	The authors met the test subject several times and received feedback	Over the course of the testing the honest criticism seemed to increase as the authors got to know the test subject.

Results:

The long-term testing procedure with subject 2 was similar as that of test subject 1. Both the test subjects received their prototypes at the same time often exercised together throughout the long-term testing. The older and more experienced test subject 2 gave a lot of well thought out feedback. Instead of contacting Exero often and spontaneous with questions, the subject often presented problems together with possible solutions. The subjects' long experience with assistive sports equipment were also valuable for the team. He was able to compare Spike with other products that he had been testing through the years. Some technical background capabilities also enhanced the value of feedback even further. The prototype worked as intended and received positive feedback from the test subject. Steering and brakes worked perfect, but sitting position and seating could be improved further.

Discussion:

The subject was seen as a "demanding customer" and seemed not afraid to present negative feedback. Over the course of the testing, the honest criticism seemed to increase as the authors got to know the test subject. Honesty from test subjects can be difficult to come by as many users seems to be afraid to hurt the ego of the developers. This effect also tends to heighten as the relationship between the authors and the test subjects develops, which did not happen in this case. This made test subject 2 a valuable asset for the development team.

Conclusion:

The test period with test subject 2 has been quite similar to test subject 1. This test subject has been more reflected and given the authors more concrete feedback. The prototype of Spear looks promising and is something that could be product number two for Exero Technologies. In this case has also observations, workshops, event testing and "thinking aloud" been conducted. The most critical part of Spear is considered to be the seating and the sitting position. This needs to be worked further with before having an acceptable version.

B-5 - Short-term user-testing

Test subject 3

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 14.03.2018

Summary:

This test was a good reality check for the authors since the test subject could not manage to get into the sled. The authors were not prepared good enough because of second-hand information. Despite this setback during the test did the test subject give much good feedback that will help in the product development. The test subject has a high spinal cord injury, and the seat was not big or strong enough to give him the needed support when transferring from the wheelchair A questionnaire was prepared but not conducted. Thinking aloud was the most used method used during this test. In conclusion, it is important to be better prepared for a test to give the best possible session. The test subject was, in general, positive and wants to test out a new version when this is ready.

Preparation and planning:

Test subject 3 contacted a member of Exero through their Facebook page and scheduled a meeting in February 2018. The Exero member communication with the subject was not a part of the development team, and limited information was passed on to the authors. The main information received by the authors was that the user had a relative high spinal cord injury. The indoor running track at Leangen Icehall was selected as test site due to poor weather conditions outdoors. Tools, parts and a questionnaire were brought along to the test. The session was an example of testing with minimum information and knowledge of the test subject.

Purpose of the test:

- To meet a new potential user of Spike
- Discover if people with high spinal cord injury would manage to operate the product
- Test the new width-adjustable seat prototype, assuming enough time and that the test subject could operate the product in a acceptable manner

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**
See if the test subject could get into the sled	He couldn't get into the sled. The current seat is to small.	The authors were not prepared good enough. Should have brought along a seat with more support.
Get feedback on the new seat	Didn't get the chance the new seat, but he gave valuable feedback on how this could be made to fit his demands.	In general was the seat not deep enough for him to transfer from wheelchair to the sled.

Results:

At 14. March 2018, the testing occurred at Leangen Icehall, were the subject showed up with a parent. An introduction occurred, and the subject explained that he contacted Exero as he had heard about the company through friends. He then continued with explaining his injury which was a high waist paralyzing due to an accident five years ago. The subject was familiar with the knee sitting sit-skis and therefore the positioning of Spike as well. However, he quickly mentioned that he was skeptical to how he would manage the transition from the wheelchair to the prototype. The seat was specially mentioned as smaller than what he was used to. The way of entering Spike would be first to position the knees and then fasten the hip. The subject explained that due to his condition he would prefer doing it in the opposite direction. This would require a seat big enough to support the whole body in an upright position before positioning the knees.

He had heard about Exero and Spike from friends and was eager to check the prototype out. First the test subject and the authors introducing each other. The test subject told about his injury, which was a high waist paralyzing after a motorcycle accident a few years ago.

He had used a cross-country sit-ski a couple of times and were familiar with movements similar to manage with Spike. Already before he tried to get into Spike did he mentioned being skeptical if he could manage to transfer from the wheelchair and into the sled. Especially the seat was in focus and were considered too small for him to use. Usually, would he get into the sled by mounting himself to the seat before arranging the legs into the right position. This would require a seat big enough to support the whole body in an upright position before laying the legs beneath the seat. Unlike the usual way to enter the sled, where the users would place the knees and legs first before sitting down on the seat. The seat angle was adjusted into a more horizontal position with the aim to ease the transfer from the wheelchair.

Despite the concerns, the test subject wanted to give the seat a try. With help from his parent, he managed to transfer from the wheelchair and into the sled. The authors observed that the injury led to the subject having less mobility compared to experience with previous subjects. When the subject tried to enter the prototype, it became clear that the seat was too small and not suitable to support the body when entering. The seat was not able to support the body until the knees could be correctly positioned. The testing therefore ended shortly but continued with discussions. The subject was still positive to the concept, and the authors then encouraged thinking aloud about possible improvements. After some discussion, the parent also tried Spike and where positively surprised by the comfortable sitting position. She expressed that she thought this would work for the test subject as long as the seat is improved for mounting.

Discussion:

The authors learned a lot from this session. The lack of knowledge before the test led to less quality. Had the authors been more informed about the disability they could have prepared a couple of other seats to try out. The moment they met the test subject they realized that it could be difficult to carry out with the standard seat. The benefit with moments like this is a reality check of how well the product fits everyone. By constantly getting feedback, constructive or positive, the authors have the basis for making decisions. However was the test subject very positive and wanted to give it another try when the problem is fixed.

Conclusion:

It is essential to be well prepared for a testing session, however, did this test end well despite difficulties when trying the sled. By having an open mind and be prepared for scenarios like this have the authors learned a lot for future tests. The test subject had much interesting feedback, among others a bigger seat with more support. Based on this test was the seat re-designed since the authors did not see any problem making it more suitable for people like test subject 3. The questionnaire was not conducted and will be tried out in the next test.

B-6 - Short-term user-testing

Test subject 4

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 21.05.2018

Summary:

This was an example of a test with a person that had tested the sled a couple of times before at events, but not more thoroughly with a more relaxed atmosphere. The authors wanted to try out a questionnaire and to be extra prepared for the test. This preparation gave results by having a successful test with both proper documentation and constructive discussions with the test subject. The test subject has been positive every time Exero have met him and this continued during this test where he also gave a top score of the product in the questionnaire. It should be discussed how honest he could be when giving such a high score, but nothing indicates that he was not telling the truth seen from his point of view. This is considered to be one of the best conducted and can be seen as an example to follow in the future.

Preparation and planning:

This test subject had met members of Exero several times previous, mainly different assistive technology events. He had previously tried the prototype two times, during an activity camp at Valnesfjorden, and during an activity day hosted by NAV. Both times were under hectically conditions and in short duration. He had, therefore, several times presented his interest in testing the prototype further. Testing was therefore scheduled in may with a more relaxed atmosphere and more time at hand. The test site would be the parking lot outside Leangen Icehall. The authors lay extra effort in to be prepared and double-checked everything on the sled before arrival. Necessary tools and spare parts were also brought along.

Purpose of the test:

- To meet a new potential user of Spike to find out if his disability could manage the product.
- Test out questionnaire as a method for evaluate the test
- Get feedback on new belts and the latest design concept of Spike

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	Result:	Comments:
Give a proper test of the current prototype	This went very well. He managed the sled in a good way and tested out features that he hadn't been tested before.	Nothing special to comment.
Discuss how this could be used in his everyday life	He felt that this could replace his current sit-ski which he had used just a couple of times. He saw no problem getting this covered from the "Hjelpemiddelsentral"	Interesting that he mentioned that he could give back his current sled and apply for Spike.
Conduct a questionnaire	He answered all questions with max score, only exception was the design of the current prototype which received 3 out of 5 points.	He might be to positive? Based on what the authors observed he definitely managed it well, but still

Results:

At May 21 the two authors met the test subject at the designated location. As all parties had met several times before, the conversation quickly became about ideas for changes the subject had thought out after the last testing. As there were two researchers present, one was able to converse with the subject while the other prepared the prototype. After making the appropriate adjustment, the subject mode himself from the wheelchair to the prototype. Due to the subject functionality and mobility, the subject was able to perform the transition without any problems. The test then proceeded with the subject trying the sled with different truck adjustments. The springs in the front trucks and back were tightened in the different positions. The effect of only adjusting the front truck was also tested. After trying out several settings and combinations, the subject was asked to move around in a part of the location consisting of cobblestone. The subject explained that he was something he had not been able to do with his current sit ski roller-skis. Since his last two times testing were quite reduced, he wanted to test out different truck settings to see the potential in turning radius. After trying out several settings and combinations, he was asked to move around in the more rough part of the parking lot. One part of the parking lot was covered in cobblestone, and this was something he had not been able to do with his current sit ski with roller-skies. The final part of the test was a questionnaire where the test subject was asked eleven questions with a score from 1-5. During this questionnaire, the test subject was shown renderings of the final product and asked about his opinion. The session ended with a plan of meeting again when the final solution was ready.

Questionnaire:

Questionnaire, Test Subject 4
Date: 21.05.2018

The survey completed by the test subject consisted of 11 items with the following choices of responses: 1 = strongly disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, 5 = strongly agree. The items were as follows:

Question	Answer
1. I could easily complete the task with the device.	5
2. The device helps to increase mobility and exercise of the body.	5
3. It was easy to understand how to operate the device.	5
4. The device was comfortable to use.	5

5. Using the device felt safe.	5
6. Aesthetically, I like the overall look of the planned version of the product	5
7. Aesthetically, I like the overall look of the prototype	3
8. I think the idea behind how the device is meant to operate provides a good solution to problems that I encounter with training today.	5
9. It was easy to see how I can use this device in training or recreation in my daily life.	5
10. Compared to other products I use for training, the actual functionality of this product is better.	5
11. I would be happy to buy and use this device if it were available for sale.	5

Discussion:

The general feedback was positive. He felt comfortable and liked the sitting position. The possibility of changing trucker settings where something he appreciated, and he asked if it was possible to make an easier way of doing the adjustments himself when being seated in the sled. The test subject gave a top score on the questionnaire and compared most of the answers with his current equipment for training. The new design received a good response with a score of 5, compared to the current prototype which received 3 in score on design. The authors used observations in combination with conversation and "thinking aloud" during the test. It was easy to communicate with the test subject, and he pointed out several things that could be implemented in the final solution.

Conclusion:

This test was a success and was conducted quite as planned. By having two test leaders at the place, did they manage to discuss with the test subject and do changes to the prototype at the same time. A questionnaire was conducted and received a high score from the test subject. It could be considered how honest the test subject was since he gave a top score on almost every point. However, did he also manage the prototype well, and he has been positive every time he has met Exero Technologies. It is concluded to test out questionnaires more and to always be two test leaders at the place when this is possible.

B-7 - Short-term user-testing

Test subject 5, test 1

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 03.09.2018

Summary:

This test aimed to see how a young para-athlete would handle Spike and how it could help him in training as a sled hockey player. The test was conducted by one author who had trouble doing a complete test session by himself. It was difficult to both discuss with the test subject, take pictures and make adjustments to the sled at one time. Observation and thinking aloud were used, but the documentation was reduced by being just one test leader. The test subject managed the sled very well, and he saw great potential in using this device to increase strength, stamina and core muscles. Despite the limitations of being one test leader was the test considered a success and there was also planned to do a follow-up test in the nearest future.

Preparation and planning:

Test subject 5 was contacted by Exero in the fall of 2017. The authors became aware of the subject through one of the physiotherapists at the Centre for Elite Sports Research in Trondheim. Only one researcher would perform the testing procedure. This was deliberate to explore potential advantages or disadvantage of having a single researcher compared to a testing procedure with plural researchers. It was then decided that one of the authors could test with him on a Sunday in week 35. The plan was to observe and take pictures during the test in addition to make a summary of the test subject thoughts and suggestions for further work.

Purpose of the test:

- To meet a new potential user of Spike to find out if his disability could manage the product.
- Get feedback from a professional sledge-hockey player on how Spike could be used in context with sledge-hockey training.

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**
See if he could manage the sled	Yes, he managed it very well	Only adjustments were to put some more support below his short leg
How could this be used in context with sledge hockey?	He told that this could help him improve balance and core muscles.	Possible to do a test at Granåsen and film movements and use of muscles?

Results:

The testing occurred on September 3, 2017, at NTNU Gløshaugen. The test subject was very positive before he tried the prototype and expressed that he liked the concept. It was, however, a challenge to adjust the sled due to the subjects shorter leg. Some foam material was therefore added underneath the smaller foot to match the subject's physique. Due to a smaller leg affecting the weight distribution, the trucker springs were adjusted independently to compensate. All the adjustment necessary occupied the researcher and led to some waiting time for the subject. When the adjustment was completed, however, the testing could begin. Now researcher could fully focus on observing and interacting with the subject. The researcher also made some attempted to take some pictures, but with poor results as the focus also had to be on the safety and comfort of the subject. From the authors perspective, it was a bit hectic and difficult to have an organized approach to the test session. Doing several tasks simultaneously made it difficult to both document and interacted with the test subject satisfyingly.

The feedback was in general positive. He could easily see how this could help him improve strength and mobility for sled-hockey. Because of his interest in physiology and training did he suggest a new test with the final solution of Spike, where we could test how much of the upper body that is activated with this type of movement. It was also decided to do a more thorough test at one of his training session with the team.

Discussion:

Since there was only one person from Exero at place, was it difficult to both make conversation and adjust the sled at one time. The test subject was very positive before he got into Spike and expressed that he liked the concept. The primary challenge was to adjust the sled to his shorter leg. With a couple of small pillows beneath the short leg did the sled match his physique. Because of one shorter leg would that also affect the weight distribution when turning the sled. It was, therefore, made adjustments to the trucks to equal the difference from right to left. When he started to move around in Spike, the author was switching focus from observing and interacting with the test subject. Besides was it also made an effort to take some pictures but without the best results.

Conclusion:

The test answered the purpose and the test subject managed the sled well. He was in good physical condition and show great interest in how this could improve his strength and stamina. He had good control of the sled and was quickly testing the limits which he was satisfied with. It was difficult to be only one test leader, which should be improved in the future if possible. In general, it was a positive session and it was planned to do another one shortly after.

B-8 - Short-term user-testing

Test subject 5, test 2

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 15.09.2017

Summary:

This was the re-test with test subject 5, and this one was done at his sled-hockey practice. Again was only one author available for the test, but this time it was easier to observe and take pictures during the test session. The test session also included the test subjects trainer and one of his teammates which made it possible to have a group discussion. The test was a success, and all three saw potential in Spike to supplement the daily sled hockey training. Doing the test in the test subjects natural environment was considered extra valuable, and this can be used more in the future.

Preparation and planning:

After the first test at NTNU Gløshaugen, it was decided to do a follow-up test with the same subject at one of his training sessions with the sled-hockey team. The session took place outside of Leangen Icehall. The purpose was to explore possible benefits of testing in the environment of a professional training session. It was assumed as beneficial as both the coach and other athletes would be present. The researchers, therefore, planned to encourage "thinking aloud" in the group as much as possible. For the same reasons as the first test, only one researcher would lead the testing procedure. The researcher would have no focus on interactions but instead, observe how the prototype would be used in this environment.

Purpose of the test:

- To see how the test subject would use the product in his natural environment
- Get feedback from a test object and trainer on how this product could supplement today's training program.

Test procedure:

The following figure show a short overview of how the test was conducted.

What:	**Result:**	**Comments:**

Use Spike in a normal training session	Spike was better than his wheelchair in the hill-intervals	Despite smaller wheels did he manage to keep up with the person in three-wheeled wheelchair
Get feedback from the test subjects trainer	The trainer liked the concept and saw a potential of using Spike as a supplement.	Could it be possible to make a version for playing sledge hockey on wheels?

Results:

14. September 2017 the researcher showed up at Leangen Icehall and met the test subject along with his trainer and one of the other teammates. Both the trainer and teammate had heard about Spike and inspected it thoroughly. They seemed to like the concept and was exciting to see how it would perform in the training session. The session consisted of several 100m hill intervals. The test subject seemed to have more control regarding steering as the athlete in the three-wheeled wheelchair had to switch between poling and steering the third wheel. The researcher observed that while test subject in the prototype achieved a higher speed upwards the hill, he achieved a lower speed on the way down. During the session, the researcher talked to the coach about the training program of the sled-hockey players. The coach gave valuable insight into the demands of Spike seen from the point-of-view of sled hockey athletes.

The feedback was again very positive from the test subject. He told that he performed better with Spike than his regular training wheelchair when climbing the hill. He was used to be beaten by his teammate, but this time did he follow him better. It was still a little bit hard to get used to the sled, but he felt an increase in control this time compared to last time. The possibility to use more of his upper body when using the poles were again mentioned and was also backed by the coach, who saw a potential benefit with the increased range of movement with Spike.

Discussion:

During the session did the author get the chance to talk with the trainer about the training program for the sled-hockey players. Besides training in the sled on ice, it was much focus on basic strength training and endurance training in with wheelchairs. They used specialized wheelchairs with a third wheel in the front. The training session this day was interval training by climbing a 100 m long hill several times. Compared to the teammate in the wheelchair did the test subject achieve a higher speed upwards the hill and lower speed down again. The test subject seemed to have more control regarding steering since the guy in the wheelchair had to switch between poling and steering the third wheel. Downhill did the wheelchair achieve more speed because of the large wheels.

By having all three gathered where there more "thinking aloud" than just the test subject alone. The author could observe from the outside while the three discussed themselves the product. Since it was the second time, the test subject tried the product it was easier to be just one author to conduct the test. The author could focus more on observe rather than interact and help the test subject.

Conclusion:

This test was more comfortable to conduct with one test leader, mostly since the test subject was more familiar with the sled. Observation and group discussion were used during the session and were considered successful. The test subject was still positive and expressed that he liked the prototype. Performing a test like this in the test subject natural environment was seen as valuable and should be done several times.

B-9 - Workshop

Seat workshop

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 13.11.2017

Summary:

To test out several methods for feedback on the product development was a workshop held to gather several persons with a different background. The workshop was decided to deal with the seat, which is considered to be one of the most critical components in the product. Three participants were invited to the workshop in addition to two members from Exero Technologies. Two of these were potential test-users and one physiotherapist from St.Olav hospital in Trondheim. Preparations were considered to be an essential factor for success, and this was done thoroughly before the workshop started. The session was considered to be a success, and several factors were pointed out by the participants. Workshops are seen as a valuable test method if the necessary preparations are done. It is essential to find the right combination of people to attend and to ensure that they all can contribute to the planned tasks. In general was this a success and this should be conducted more in the future.

Preparation and planning:

The purpose of the seat-workshop was to get feedback on the current prototype of the seat, and the use of memory foam. This part of the product was considered to be one of the most crucial and the development team wanted to ensure valuable insight. It was theorized that calm setting of several motivated users would give more knowledge compared to short tests. As the seat needed to be designed while avoiding pressure ulcers, a physiotherapist was invited as well. Even though Exero had some knowledge on the subject, a physiotherapist would be able to indicate the medical side of the solution. There are also physiotherapist deciding if users are allowed to receive different assistive equipment in the NAV system. It is, therefore, crucial to developing equipment that is seen as valuable from their point-of-view. In the literature, it is mentioned both benefits and disadvantages of involving people outside the product development early in the process. The authors considered this as a good opportunity to test out how that could affect the process. It would also be interesting to see the users reaction to discussing solutions in the presence of a physiotherapist. This was also the first workshop held by Exero, and it was interesting to find out if this could be a valuable method to continue with.

Purpose of the test:

- Show, test and get a first impression of the seat from two potential users and one physiotherapist
- Discussions of the participants previous experience with seat and pillows
- Encouraging Thinking aloud about potential solutions that could be developed further
- Observing the interactions between a skilled medical worker and users within a group

Results:

The workshop took place in the Exero office at NTNU with one of the authors and one other team member of Exero. After introducing each other, the author explained the agenda for the workshop for the participants. First, the author wanted to show the current concepts of both the width-adjustable seat and the memory foam. All three participants tried the prototypes and gave their opinion. The seat was attached to one of the prototypes of Spike to make it possible to sit down and try it. The memory foam was a simple piece of a pillow that was laid upon the seat to create support and avoid pressure ulcers.

After getting feedback on the simple prototypes, the author showed the participants how a final solution could look like with CAD-drawings. Then was the discussion moved on to different parts of the seat, like arrangements of the belts and where to place the brake handles.

The workshop lasted for about 2,5 hours, and all participants seemed satisfied with the event. The author got the chance to show all concepts that were planned, and the participants were eager to share their knowledge and opinion about them. They specifically mentioned some possible improvements regarding the geometry of the seat. The participants positively received the set-based width-adjustable seat. Both subjects and the participants suggested adding the seat-adjustment as a permanent feature to Spike. They all agreed on the difficulties of being fastened tight enough to excising cross-country sit-ski sleds and believed this could be a valid solution.

Discussion:

Based on feedback from participants the workshop can be seen as a success. From the authors' point of view where most of the planned topics discussed during the workshop, however, was there a lot of new information that also came out. There wasn't planned to have a session with questions or thoughts randomly from the participants. It could be strategic to do this next time, by leaving some time dedicated to talk about ideas and thoughts from the participants. As always are there changes to the plans and in this case, the leaders of the workshop handled this in a right way. By having people that were familiar with the project and the people in Exero Technologies, the atmosphere was relaxed, and the session felt creative. It can be discussed if the people gathered were the right one and if it could help to bring new people in next. So far it seems to be important to bring people that care and wants to contribute to the project.

Conclusion:

In conclusion where the participants happy to be invited and they were engaged during the whole workshop. The author was also left with a good feeling and was motivated to work further with the concepts. This method was seen as a good way of motivating for thinking aloud and as an arena for letting the right people giving their thoughts and feedback.

B-10 - Workshop

Workshop in a users' environment

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 26.04.2018

Summary:

This was the second workshop conducted during the master thesis and was conducted with test subject 1, test subject 2 and the father of test subject 1. The authors focused on a few things to test out, based on experience from the last workshop. To bring a new dimension to the workshop, it was planned to be done in the home of one of the test subjects. The main purpose was to get feedback on the new pillow prototype and general feedback from the test subjects long-term testing. Also, did the authors get a tour to see where the test subjects live and train in their daily life. The workshop led to several points for further work and especially the father of test subject 1 contributed with relevant information.

Preparation and planning:

The workshop was planned as a follow-up inspection on the prototypes given to test subject 1 and 2. As well as performing an inspection, short-term tests would also be performed. Feedback and observations would be evaluated against a short-term test performed previously in the pre-masters project. As both test subjects had visited the Exero office several times, it was suggested that the author would visit the subjects' hometown instead. This presented the possibility to observe the subjects in their environment and everyday life. However, it also made the planning for the testing more difficult.

Purpose of the test:

- Test and get a first impression from test subject 2 regarding the pillow-prototypes
- Discussion of experience during short-term and long-term testing
- Observing and learning about the test subjects everyday life

Test procedure:

Planned time scheduled for the workshop:

- Inspection and maintenance of the prototypes 15 minutes
- Short-term testing 20-minutes
- Discussion and feedback of short-term testing 15-minutes
- Discussion and feedback of experiences during long term testing 25-minutes
- Observations of the subjects everyday life at home and a the gym 45-minutes

Results:

The testing procedure for the workshop did not go according to the pre-planning. Instead of visiting the subject for two hours as scheduled, the workshop lasted for five hours in total. The first abnormally to occur was an additional participant. The location of testing had been chosen by the participants to be at the home of a parent of test subject 1. This lead to the parent was also joining the workshop. All though not a part of the plan, the parent, with a mechanical background and a passion for sports, was a valuable participant in the conversations. The authors were also informed that during the long-term testing, the parent had often participated by riding a bike next to both test subject 1 and 2. Observing them over such a long period presented a unique insight not previously available for the authors.

During the short-term testing, the pillow-prototype was tested on the Spear prototype of test subject 2. The subject tested all three prototypes Roho, Memory Foam and SBS-1. All the pillows were first tested while being stationary, then while using the prototype actively. The Roho-seat was recognized by the subject as he had tested it before with a negative result. Even though the Roho-seat was tested among the other prototypes, it was quickly rejected by the subject. Previous experience had shown that users' thoughts and trust considering a product often predetermine the feedback they may present. For each change of seating the subject had to get out of the prototype, back into the wheelchair and vice versa. The process seemed tiresome, as the subject was paralyzed. A comfort-score one, a scale from one to five, was given on each of the prototypes:

- Roho - 1
- SBS-1 - 3
- Memory foam - 5

When testing out the memory foam, the subject was given highly positive feedback quickly after trying it out. From the pre-masters project, the authors were aware of quickly positive feedback is in the danger of being exaggerations. The statement, however, was backed by the parent which through his experience of observing the subject, noticed a significant improvement in the subjects' posture. Test subject 2 then tested the pillow while actively using Spike. While doing so, test subject 1 and the parent actively discussed benefits and disadvantages they saw in the new material. During this process, the authors stayed as passive as possible. Giving them the ability to talk freely let the authors discover the areas which seemed important to the subjects. However, the discussion would also go off topic once in a while if the authors did not intervene. Being approximately 6 months from since last testing session with the subject, made it difficult for the authors themselves to recognize any major differences on the subjects handling of the prototype. Some improvement was however discovered through giving the subject the same questionnaire as the last session.

Discussion:

During the workshop, the authors noticed comments from test subjects 1 father that was not aligned with the test subjects statements. By having a closer relationship with the test subjects, could he disagree in the other way than what would be proper for the authors. Having the test subjects close friends and family brings a new dimension to the discussions and “thinking aloud” sessions. It could be discussed how test subject 2 rejected the Roho pillow without trying it out in the sled. It might be possible to test the pillow out with another test subject to get more feedback. As mentioned before are both of these test subjects quite straightforward, and from previous experience, this could lead to some hasty decisions.

Conclusion:

In conclusion, the workshop gave the authors a lot of inputs. Compared to the effort by conducting the workshop, where it considered extremely valuable. From the theory, the authors had the chance to observe, think aloud and focus group. The overall atmosphere was good and the authors left with increased enthusiasm. By having people with a close relationship in place, the authors could receive feedback from a third-party. This made the authors aware of user needs that not necessarily had been brought up otherwise. The father of test subject 1 had several observations that were considered interesting to pursue further. He did also disagree in some of the statement made by the test subjects. This led to further discussions and several points of view.

B-11 - Event testing

Ridderrennet

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 17.03.2018

Summary:

Ridderrennet is an event that Exero Technologies have attend two times before. This is the largest event of its kind in the world and a natural place for the authors to attend. The goal was to get feedback on design and hopefully get someone to test or plan to test in the future. One of the authors traveled to Beitostølen 16 March with one other team member of Exero Technologies. The event did not go exactly as planned, partly because of too little preparations. Receiving feedback on design, however, was considered a success and this is something to work further with in the future. As for testing of the product, it was less valuable because of too little time with each potential test user. Instead, the authors got several tests planned for the next couple of months which is a good result.

Preparation and planning:

The purpose of attending Ridderrennet was twofold. The goal was both to test with users at the location as well as networking and find users for more thorough testing at a later time. The size of the event makes it a great platform for meeting potential users for testing. There was also a goal to get feedback on the visual design of the product. An event like Ridderennet has a large flow of people which would give many different "first impressions" of the design. At this stage the all-around visual design of the product where close to being finished. As this was the third time Exero visited the event, the team members had some expectations of how it would occur.

The Spike prototype was re-built back to an older version. None of the prototypes mentioned in this thesis were brought to Ridderrennet. Previous experience had shown that the testing time available with each user was limited to such events. It was therefore assumed that a more well-known version of the prototype would lead to a more natural testing process. The analytical model of Spike was colored and rendered. Rendering is a time-consuming process but gives a much more lifelike impression compared to a sketch. The rendering was created to be able to get feedback on the design. Informative flyers were created to hand out to people passing by. The flyers contained a simple description of the product and contact information. Sign-up form for people to write down their contact information to able us to make contact at a later date was also made.

List of preparations done:

- The Spike prototype were re-built back to an older version. None of the prototypes mentioned in this thesis were brought to Ridderrennet. Previous experience had shown that the testing time available with each user were limited on such event. It was therefore assumed that a more well known version of the prototype would lead to an easier testing process
- The analytical model of Spike were coloured and rendered. Rendering is a time-consuming process but gives a much more lifelike impression compared to a sketch.. The rendering was created to be able to get feedback on the design.
- Informative flyers were created to hand out to people passing by. The flyers contained a simple description of the product and contact information.
- Sign-up form for people to write down their contact information to able us to make contact at a later date.

Test procedure:

Two members of the Exero team (one author included) would travel from Trondheim to Beitostølen the day before the race on March 16. The day after they would assemble a stand near the finish area of the race. Exero had borrowed tent and tables from the organizers on arrival the two previous years. It was therefore assumed, the same would be possible this year. Due to the little advancement of the Spear prototype process, only the Spike prototype would be presented on the stand.

Results:

One of the authors and another team member in Exero was chosen to attend the event and traveled down to Beitostølen, March 16. Ridderrennet was held March 17, and the author used the morning to set up a stand where people could see the prototype and rendered pictures. The borrowing of tent and tables did not go as expected. This year the organizer did not have as much equipment as usual and could not promise either. As no such equipment had been transported from Trondheim.

Discussion:

The preparations were not so good as the year before where Exero had lent a tent from the Norwegian Army to create a better stand. This made the appearance less noticeable, but there were still a lot of people coming by. It was quickly noticed that people had feedback on the rendered pictures both constructive and positive. There were many people present and the main event, cross-country ski competition, were naturally a highlight. This made it difficult for potential test users to find the time for testing the prototype of Spike. A couple of people were interested and took the time to test. However were these tests not so good, mainly because of limited space and snow on the ground. Both the author and the test users noticed the drawback with this, and some of them asked if they could meet Exero at a more suitable place later.

Conclusion:

In conclusion was the event considered successful from a marketing view, with a lot of people being exposed to the prototype and the company. However, from a product development point of view was it seen as less successful. The few people that actually had the time to try the prototype had poor conditions to move around. The most useful from a product development view was feedback on the rendered pictures. It was something that engaged people and in general was the feedback positive. Compared to last year was not the author prepared good enough, something that led to a less successful session. An event with so many participants needs proper preparations to get useful results.

B-12 - Event testing

Wings for Life

Participants:

Bendik Fon
Mathias Berg

Test report for the master thesis:
Prototyping and Testing During an Assistive Sports Equipment Development Process

Date: 06.05.2018

Summary:

Wings for Life was a perfect place for testing out the prototype of Spear in a real competition. This was the second time Exero Technologies attend Wings for Life with a test subject in a prototype. The goal was to give the test subject and prototype a real challenge with a couple of new adjustments. Pillow and mudguards were re-made and tested out with a positive result. The test method used was mostly observation from one author that followed on the bike and thinking aloud with the test subject after the event. The whole experience was a success, and the authors could concentrate and observe how the prototype handled different challenges. Based on time invested this is seen as a valuable way of testing out a prototype in a natural environment.

Preparation and planning:

The Wings for Life World Run is a running competition with the aim to collect money to research on curing Spinal Cord Injury. The event is held every first weekend in May and is taking place in around 35 countries. Exero Technologies participated in the event in Stavanger 2017 where Aksnes used a Spike prototype. The event was a success, and the authors wanted to do a new test in the 2018 version. Exero Technologies and Red Bull was the host for the 2018 event in Trondheim. All of the potential test users from Trondheim where invited and two of them had the chance to participate, Andresen and one person that had tested Spike in the fall of 2017. Andresen was doing the competition in the prototype of Spear and the other person with his standard wheelchair. The authors saw this as an opportunity to conduct an extensive test of the prototype and test out a couple of adjustments. It was chosen to test the new pillow-prototype (improved from the workshop) and prototypes of mudguards.

Purpose of the test:

- Test the performance of Spear in a competition scenario on different terrain
- Test the performance of memory foam pillow prototype during a competition scenario

- Test the performance of the last version of the mudguards made through rapid prototyping

Test procedure:

List of preparations done:

- Performing maintenance on the Spear prototype to ensure the safety of the test subject
- Build a new an improved pillow-prototype and mount it to the Spear prototype
- 3D-printing the latest revision of the mudguards and mounting them to the Spear prototype
- Gather spare parts for all crucial elements of the prototype, e.g., wheels and braking fuel

Results:

The event was held on Sunday, 6 May near the center of Trondheim City. The course was about 3,6 km and consisted of asphalt, gravel road and cobblestones. It had two quite steep hills which were used both ways in the race. This made it possible to test and observe the prototype in quite challenging surroundings. One of the authors was chosen to bike along Andresen all the way, both as support and to observe the test. The other author was placed at the start/finish point of the course to assist in the turning in the end and bring water and other supplements.

The concept of Wings for Life World Run is to be overtaken by a "Catcher Car". The participants get a 30 min head-start before the car starts and step by step increase the speed when the car "Catches" the participant he/she are out of the race. The goal is to get as long as possible before being overtaken. Andresen had a personal goal to reach 13 km in the race. Right before the race, the authors mounted the new pillow and mudguard on the sled. Andresen was satisfied when he first sat down, and he wanted to give it a try in the race. The first couple of rounds was used to get familiar with the new pillow and the track. Andresen seemed to have good control, and the authors noticed that he was getting more and more comfortable during the race. The pillow worked as intended where the memory foam formed itself to the body of Andresen.

Discussion:

The author that followed Andresen with the bike had a unique opportunity to observe how the sled handled different challenges along the track. The transition between asphalt, gravel road and cobblestones worked perfectly. The most challenging parts where the uphill on gravel and the 180 degrees turn at the end. The other author where station at the end to help with the 180-degree turn. Despite being hard going uphill, Andresen gained even more by getting high-speed downhill. He had good control and could maneuver easily between obstacles by leaning from side to side. Andresen finished after 25 km, almost twice as his goal. He was extremely satisfied and was very happy with the whole experience. The mudguards worked as intended, but they were only mounted in the front. This must also be implemented at the back in the future, based on the mud splashed on the test subject.

Conclusion:

In conclusion, the event was successful, and the test of Spear worked well. From the theory, the authors had the chance to observe, think aloud and conduct a usability test. From a product development view, it was an excellent opportunity to see how the sled worked in a competition setting with a high demand for reliability. Another significant result of the event is the marketing and publicity that follows and creates more attention from potential test users and buyers.

Appendix C

Ridderrennet - Flyer

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Appendix D

Ridderrennet - Sign up form

Spike

Navn

E-mail

Telefon

By

Er dette et produktet du kunne tenke deg å søke på i fremtiden?

RIDDERRENNET

exero Technologies