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New slopes - Designing a motorized cross-country sit-ski to increase accessibility, safety, activity level, and fun for paraplegic cross-country skiers

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Abstract

In modern times the activity level also of the paraplegic population has decreased due to changes in everyday life. The paraplegic population desires to be more active but are not given the opportunity, esp. in nature. The prepared cross-country slopes pose impossible challenges with steep slopes that are impossible to climb and outright dangerous to decent. Using universal design principles, we designed a motorized sit-ski that makes the available cross-country ski infrastructure finally fully accessible for the paraplegic population. Results show that the proposed design enables poling uphill without the need for assistance and reduced speed downhill with increased safety, thus giving paraplegic the opportunity of freedom, independence, increased activity, and the opportunity to explore nature together and on par with the general population.

Keywords: prototyping, engineering design, experience design, healthcare design, product design,

1 Introduction

According to the World Health Organization, health problems are more widespread than ever, and worldwide obesity has nearly tripled since 1975 (*Obesity and Overweight*, 2020). The sedentary nature of work tasks, changing modes of transportation, and urbanization have led to a decrease in physical activity. In the world, 75 million people need a wheelchair daily (‘Paraplegic People in the World in 2019’, 2019), but there are few activities customized for wheelchair users, except for the use of a wheelchair. Cross-country sit-skiing is regarded as an excellent way for people with mobility impairments to enjoy the outdoors and movement of the sport of cross-country skiing (*Medical Home Portal - Adaptive Skiing*, 2018; *Nordic Adaptive Sit-Skis Bring Freedom to Mobility Impaired Persons*, 2016).

Research on the role of exercise in mental health in the general population has increased in the past 15 years (Fox, 1999). Physical activity contributes to greater self-esteem and self-confidence, better cognitive functioning and mood, maintenance of normal sleep rhythm, and stable mental health (Miller et al., 2016; Pilipović Spasojević et al., 2020; Rajati et al., 2018). In later years, there has been a change in the mindset of people, leading physical activity to be an important aspect of everyday life. Individuals have to make an active choice to stay in physical activity to remain healthy. An increasing number of people with disabilities are involved in adaptive sports (Gastaldi et al., 2016; Rajati et al., 2018). Research has shown that 82% of paraplegic people would like to be more active, and only 40% feel they are given the opportunity to be as active as they would like to be (*Facts & Statistics | Activity Alliance | Disability Sport*, 2020). Paraplegic adults are twice as likely as non-paraplegic adults to be physically inactive (*11 Facts About Physical Disability | DoSomething.Org*, 2014). Researchers from the U.S. Centers for Disease Control and Prevention found that 47% of those with disabilities aged 18-64 get no aerobic physical activity, and another 22% get some exercise but not enough (*CDC*, 2014). Physical activity is seen to preserve residual functions and prevent further complications or injuries for wheelchair users. It is a great opportunity for social reintegration and has proved to give positive effects on health, overall well-being, and quality of life (QoL) (Gastaldi et al., 2016; Pedersen et al., 2021). For individuals with disabilities, activities often entail additional challenges that require more customized equipment. The adaptive outdoor sports have been widely enlarged during the last two decades, owing to global advances of assisting technology and personal training (Gastaldi et al., 2016).

A cross-country sit-ski (CCSS) consists of a chair supported with a suspension over a pair of skis. The chair has strapping to secure the skier to the sit-ski for mobility and safety. Regular ski poles are used for propulsion and serve as steering tools and braking in downhill situations (Rapp et al., 2013).

Figure 1. Skeno Power by Skeno AS

Sit-skiing is a strenuous activity, requiring significant upper body strength ("Cross-Country Skiing," 2021; Lund Ohlsson et al., 2018). On a general basis, the focus on the equipment in high-speed sports is weight reduction of the equipment (Lei, 2021). However, the action of weight reduction is not enough in itself to engage non-athletic users, as considerable arm strength is required. Research has been done to explore the external power output of roller sit-skiing on a treadmill to find the force required in different slope gradients (Pellegrini et al., 2011). A relatively small change in slope grade requires a significant increase in power production. Supporting equipment exists for an able-bodied companion to assist with pushing force, but this affects the feeling of independence of the sit-skier.

The high velocity a sit-ski user can achieve in downhill skiing is a problem. As a result, some sit-ski designs offer brakes as an additional item to improve the user experience and provide a sense of control. However, braking and steering are two functions that are difficult to perform simultaneously.

1.1 Sit-ski courses

There is a significant difference concerning the layout of the ski trails between able-bodied skiers and sit-skiers. In general, a competitive Nordic ski trail should consist of 1/3 uphills, 1/3 downhills, and 1/3 undulating terrain. The following additional points should be considered when designing courses for the sit-ski competitions as regulated by the World Para Nordic Skiing Homologation Guide (*Nordic Skiing - Rules and Documents*, 2020):

Downhills should have a straight run-out, preferably with a slight uphill to break the speed.

- A-hills: 10-15m Partial Height Difference (PHD), 4-12% gradient
- B-hills: 4-9m PHD, 4-12% gradient
- C-hills (short hills): 2-4m PHD, distance < 30m long, gradient > 12% maximal 16%

The same design courses for able-bodied skiers can be summarized as (*FIS Cross-Country Homologation Manual*, 2019):

- A-hills: PHD > 30m, 9-18% gradient
- B-hills: 10-29m PHD, 9-18% gradient
- C-hills: 4-10m PHD, gradient > 18%

There is no upper limit of the C-hills gradients for able-bodied skiers. Most cross-country ski trails worldwide contain C-hills due to local terrain, steeper than legislated for competitive CCSS trails. It is evident that if a local recreational ski trail is designed for able-bodied users, sit-skiers will often have difficulties using the trails due to steeper and longer climbs than they can overcome.

2 Method

An experiment was designed to compare the tractive performance and the braking effect of a commercial cross-country sit-ski (CCSS) and a prototype of a sit-ski with motor assistance for enabling exersise. Users include both able-bodied and paraplegic test persons. This section describes the method used for designing the experiment, including the equipment used, experiment procedure, and metrics for evaluation.

2.1 Prototype with propulsion enabling new slopes

A prototype of a novel design of a sit-ski with a motorized belt drive system has been developed, aimed to help with propulsion assistance uphill and braking in descents. The intention is to make the sport available to more users and engage new users to participate in recreational activity. Comfort was a design criterion, where knee and leg rests were important components to prevent pain and reduce risks of injuries.

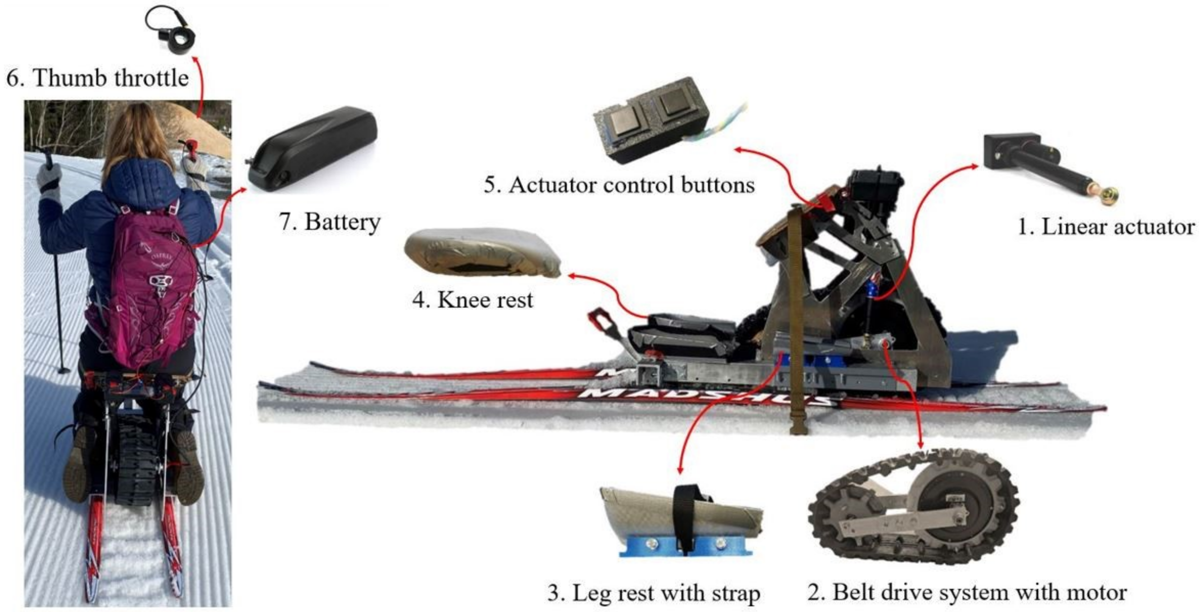

Figure 2. Components of the prototype

The design of the prototype was an iterative process, using a combination of product development theories. A set of solutions were researched and explored in a combination of set-based and point-based design approaches (Jensen et al., 2017; SINGER et al., 2009). Sketch drawings of possible solutions were made, and the work was done based on the wayfaring model (Steinert & Leifer, 2012). The evaluation was based on tractive force, similar successful technologies, and aesthetic design.

The design differs from the existing CCSS by having a motorized belt placed under the seat. The motor used is an electrical bicycle motor, with speed regulation through a thumb throttle mounted on the ski pole. Two linear actuators ensure a raising and lowering mechanism of the belt, allowing the user to pole with or without assistance from the motor. The positions of the actuators are controlled by two push buttons located under the seat. By controlling the actuators, the snow penetration can be used to optimize propulsion for different snow conditions. The tractive performance of vehicles on snow is affected by the material properties of snow, as it is a rapidly changing and unstable material (Pytka, 2010). The intended use of the design is for exercise. The motor assistance can be adapted to fit both experienced athletes who need little to no assistance, and beginners who do not have the ability to pole with considerable effort. In addition to helping users overcome hills, the prototype has an assistive resistance braking system designed to reduce the speed downhill by rolling resistance and friction from the belt. The prototype was mounted on suboptimal Madshus 119 Nanosonic series soft skate skis, not prepared for speed.

2.2 Test trails

An alpine slope trail was chosen to test the motorized sit-ski, with a slope gradient steeper than what is determined as the maximal slope gradient for competitive courses by the World Para Nordic Skiing Homologation Guide. The upper limit for the steepest slope gradient hills (C-hills) is 16% for para courses. In able-bodied ski courses, there is no maximal limit, but the PHD is limited by 4-10m. The measured steepest gradient in the alpine test slope was 23.1% with a PHD of 4m and would be characterized as a C-hill for able-bodied skiers.

To be able to measure the performance, a precision electronic measuring device by Microgate; Witty Gate photocells, and Witty Timer receptor was used. The photocell placements (W-1-W5), laps between measuring points (L1-L4), as well as slope gradients, can be seen in Figure 2 and Figure 3. A short distance between L1 and L4 in Figure 4 permits measuring the start and end velocity. A longer distance, L2 and L3 in 0, enables average velocity measurement.
First, the test persons used the CCSS to pole as far up the alpine slope as possible. If they reached the top, they were also asked to ski the slope downhill. Then they performed the same test with the prototype. Total lap times of the test of 85m were compared to give an impression of how the prototype can be used as a regular sit-ski, where the importance is to maintain the feeling of joy of the activity. Another crucial result from the test experiment is the evaluation and feedback from the test persons. A Skeno Power state-of-the-art sit-ski mounted on glided Madshus Skate Race Speed (182cm, 60-75kg) was used to compare the prototype in the experiment.

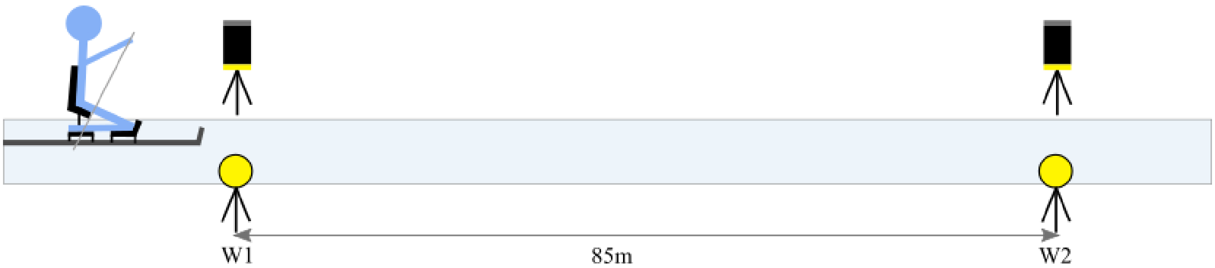

Figure 3. 85m straight stretch test course.

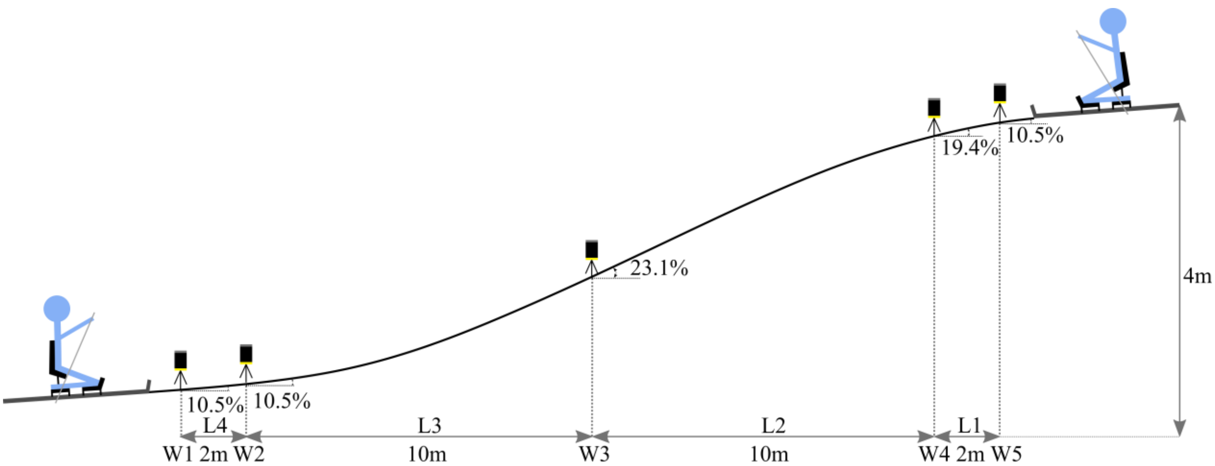

Figure 4. Alpine slope test course.

2.3 Test persons

Participants were recruited from Beitostølen Healthsports Center (BHC), a rehabilitation center offering publicly funded, secondary rehabilitation stays to children, adolescents, and adults with disabilities (Gjessing et al., 2018). Both professionals at BHC and patients took part in the experiment. Seven users with an age range from 23 to 46 years participated in the research. Users 1-5 completed tests in the alpine slope. Three of the users were able-bodied and experienced sit-ski users, and two paraplegic persons were new to the sit-ski experience. Users 6-7 were able-bodied and new to the sit-ski experience; they performed a test on the 85m, 0m PHD 0% slope gradient stretch. Able-bodied and paraplegic were recruited from various users, providing objective and subjective feedback.

3 Results

The test was performed at the two different ski trails with varying snow conditions throughout the experiment, which is not believed to have influenced the test results.

3.1 Test person information

The prototype where evaluated by 7 different persons, both able bodied and paraplegic with information presented in Table 1.

Table 1. Information about the test persons

User nr.	Sex	Age	Able-bodied (A) / Paraplegic (D)	Height [cm]	Weight [kg]	Sit-ski experience	Confidence up	Confidence down compared to up
1	M	46	A	172	75	4	A	Lower
2	M	25	A	175	76	4	A	Lower
3	F	25	D	157	60	1	E	Lower
4	F	30	A	166	72	2	A	Lower
5	F	32	D*	166	66	3	H	Lower
6	F	24	A	164	57	1	A	Higher**
7	F	23	A	161	70	1	A	Lower

- From the table, *, the user had been using a wheelchair for 8 weeks.
- ** The user has professional alpine skiing experience.
- Sit-ski experience was ranked from 1-10, where 1 is equivalent to no or little experience with sit-ski, 10 the level of an Olympic athlete.
- A = confidence to ski up all hills the user can manage by muscle power.
- E = confidence easy undulating terrain.
- H = confidence more hilly undulating terrain.
- The confidence level of maximal percentage slope angle skiing uphill was categorized (A, E, or H), and the confidence down was compared as Higher or Lower than the users answer to up.

3.2 Uphill

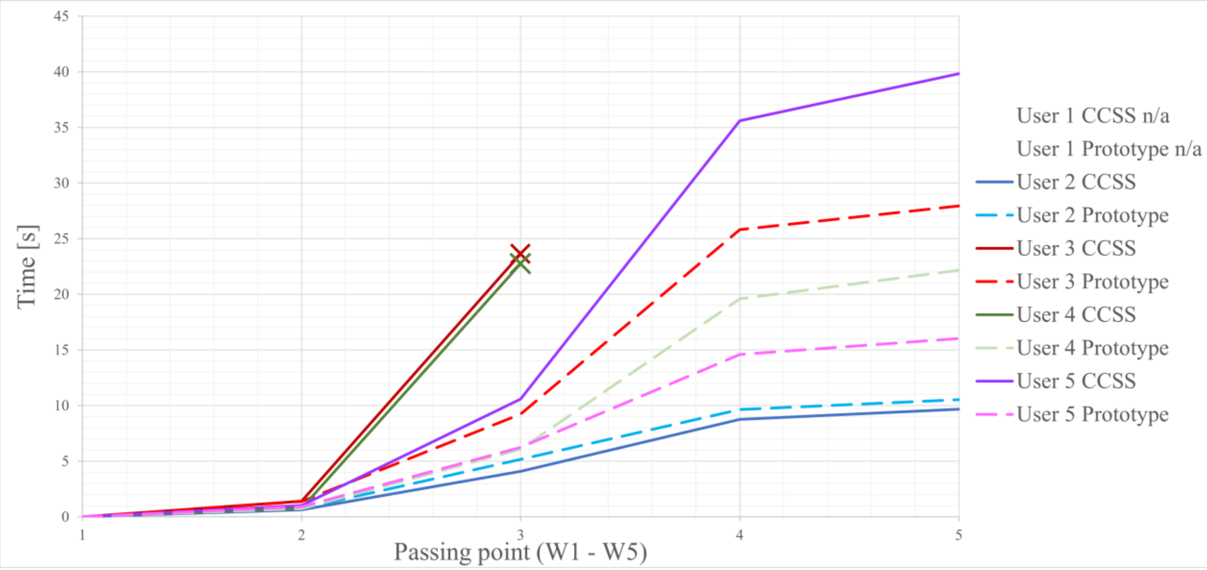

Figure 5. Time of (W1-W5) passing points CCSS and prototype going uphill in the alpine slope test course.

The two cross-marks (0) refer to the users not being able to pole to the top with the CCSS as they only reached passing point W3. The same users had no issue reaching the top using the prototype.
User 1 experienced a total loss of propulsion assistance up the alpine hill with the prototype. The user was still able to pole to the top, but the poling time was influenced by the misfortune. Test results for this user are thus not included for the two sit-skis.

3.3 Downhill

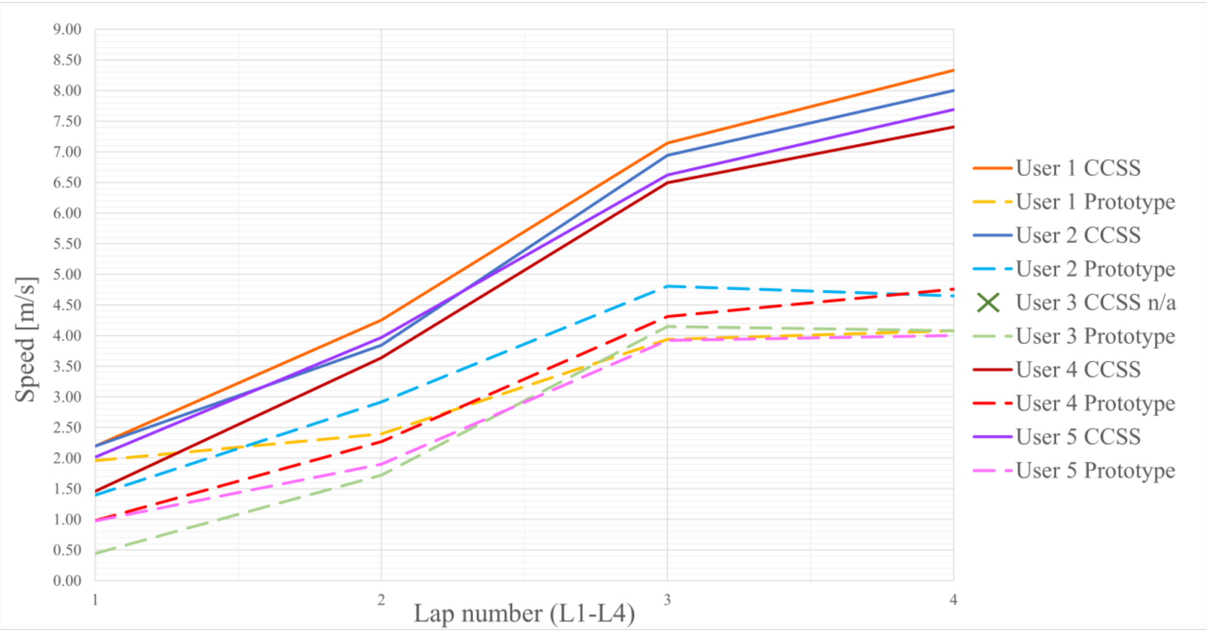

Figure 6. Comparison of speed skiing downhill the alpine slope test course with the CCSS and the prototype of users 1-5

The speed measured at the last lap (Lap 4) is the end speed of the sit-ski (Figure 6). The overall and end speed of the prototype was lower than for the CCSS. User 3 did not participate with the CCSS downhill.

3.4 Flat trail tests

Lap times of the 85m flat, straight stretch test (0) are presented in the table below. CCSS was compared to the prototype with motor speed, and with an elevated belt.

Table 2. User 6-7 85m straight stretch test results.

User	85m straight stretch course	Lap time [s]	Speed [m/s]
6	CCSS	20.99	4.05
	Prototype with elevated belt	34.5	2.46
	Prototype with motor speed	27.95	3.04
7	CCSS	21.68	3.92
	Prototype with elevated belt	21.21	4.01
	Prototype with motor speed	27.28	3.12

The poling time of the prototype with an elevated belt was longer than the CCSS for user 6 but was almost equal for user 7. The speed was lower with the prototype using motor speed than with the CCSS for both users.

4 Discussion

Physical activity is important for persons using a wheelchair, preventing further injuries, giving opportunity for social reintegration, and stable mental health. Only 40% of wheelchair users feel they are given the opportunity to be as active as they would like to be. When testing with user 5 that recently became in need of a wheelchair in daily life and providing the person a prototype design with the goal to increase the quality of life, the user said,

> "*The opportunity to go outside and get some fresh air and to be in nature means a lot to me. It is the joy of my life. When I got ill and did not have the opportunity to get fresh air, I quickly faced a wall. I became very depressed.*"

User 5 had only been using a wheelchair for 8 weeks and had already experienced that a common problem for wheelchair users is fatigue and being worn out quickly.

> "*When I got ill, I felt like I lost a part of myself. I had no joy in life. It was difficult to get out of the house and not feeling ill all the time, to meet other people and friends.*"

Cross-country sit-skiing is regarded as an enjoyable outdoor winter activity for people with mobility impairment. However, the arm strength requirement can put restrictions on the activity, scaring sit-ski users to stick to a small area of activity in case of being worn out. A professional at BHC explained that there are three available cross-country sit-ski trails in their local area. A 400m almost flat trail is located at the center, and in addition, a 2km and 4 km trail with more undulating terrain has a starting point there. A problem noticed was that some of the sit-skiers never reach the 2km and 4km trails. They are bound to the 400m trail due to fatigue, arm and trunk strength problems. The fact that the skier will never be able to explore larger areas may be demotivating and can act negatively on the feeling of self-accomplishment and independence. The trails are readily available but not accomplishable without assistance from a companion. The users can explore more extensive trails with this prototype design.

The perceived ability of a person to perform tasks successfully and confidence in skills has been shown as an important factor of health results (Craig et al., 2013). Self-efficacy has a mediating role between stress and depression and has effects against the negative impacts of pain and fatigue (Ponti et al., 2020). User 5 had low upper body strength when she started to use a wheelchair and believed that the prototype is an excellent place to start to learn the technique of sit-skiing without wearing herself out. This prototype design can potentially allow the user to perform the sit-ski activity without the presence of a companion, possibly increasing the feeling of self-esteem, independence, and confidence. From an instructor's perspective, user 4 explained that often there is only a need for a little push to help the sit-skier, even just for assuring that the skier does not slide backward when poling up a hill:

> *"Those who otherwise would not be able to get up the hills at a trip are now able to, because of the motor. One might not even need an* assistant *or friend."*

The alpine slope has a gradient steeper than indicated to be maximal for a competitive course for athletes at the Olympic level; such hills are often found in ski trails due to local terrain. Users 3 and 4 were not able to pole the alpine hill with the CCSS, but all test persons where able to pole to the top using the prototype with propulsive assistance. The general feedback of the propulsive performance was that the users would feel comfortable poling up all hills. The prototype poling time for user 5 was highly reduced.

> *"Genius! I saved a lot of energy going uphill. I saved my arms [the muscle power] and can use the energy on other things than to wear myself out on the uphill poling. I felt really safe uphill."*

A problem many sit-ski users face is the high speed the equipment reaches in downhill skiing. When a user becomes scared by the speed it is often too late to start braking. When asked about what slope gradients the users felt comfortable skiing up and down with a CCSS, user 1 answered he is comfortable poling up the highest possible gradient he can manage.

> *"The problem is that I don't dare to ski the same hills down again".*

Being an able-bodied sit-ski instructor, he knows most sit-skiers are stopped by steep descends before steep climbs. When skiing in undulating terrain, his role as a companion is to aid with propulsion uphill, but more importantly, to slow the speed of the sit-skier down descends to avoid a crash or losing control. From Figure 6, the end speed of the prototype is approximately half of the end speed of the CCSS. Without exception, the velocity of the prototype is lower than the CCSS for the entire test run. The prototype keeps the speed low from start and will reduce speed to a level where the user feels safe. The assistive resistance braking system will also generate a steady flow and avoid problems of emergency braking and inconsistent driving.

> *"I liked that it slows down so much. Then I felt like I only needed to sit still and keep my balance. That was not difficult either. I felt that the sit-ski was stable."*

User 5 who was new to the sit-ski experience reported a much higher sense of safety when the belt was slowing the speed compared to the CCSS. User 3, who was comfortable skiing descents in easy undulating terrain, found the smooth braking a lot better than traditional braking using poles. All users found the downhill speed and braking of the prototype comfortable in the steep alpine slope. The CCSS test run for user 4 ended with a crash and overturn far from the last timing point, although braking with the poles. She realized before she reached the bottom of the slope that she would not slide as far with the prototype as the CCSS did.

> *"It was nice to have that security. When the brake works so well, I managed to steer a bit better with the ski poles. I had no chance with the Skeno Power because I had such high speed that I could not turn".*

This engineering design can potentially be used for a variety of snow characters. Local weather changes are challenging as solar heating of the snow is an influencing factor causing changes in snow properties. A larger normal force is needed to maintain the tractive force as the snow weakens, and the problem can be solved by adjusting the belt position to increase contact pressure. The easily accessible actuator extension buttons facilitate optimal assistance level suiting the snow types during a skiing session.
The low-quality skis of the prototype were suboptimal compared to the skis of the CCSS and might be a reason why the poling times were longer in the straight stretch test results (Table 2). The prototype is not weight-optimized, but the weight of the equipment is only a proportion of the total weight. The weight addition is believed to be less important for physically strong and experienced athletes, as seen for user 2 in Figure 5. The straight stretch test results serve as a proof-of-concept to show that the prototype functions as a regular CCSS when the belt is completely raised from the snow surface.
The longer lap time of the prototype with motor speed can easily be fixed with a more powerful motor, but it is important to regard the design as a measure to increase the statistic of how many wheelchair users feel they are given the opportunity to be as active as they would like to be. The prototype is designed to give more people an opportunity of freedom, to be independent, explore nature and stay physically active in their local activity areas.
For the paraplegic population skiing is a heavy exersice that also requires assistance from abled bodied friends or personell. The reduction in strain on the body might also allow for new slopes, and the posibility of joining abled bodied on skiing trips. The presented engineering design allows a major part of the paraplegic to experience the fun in skiing independently and safely.

5 Conclusion

In this article, the engineering design of a motorized CCSS has been described and evaluated using both subjective and objective test results. The results shows that in sit-skiing, the speed downhill is a greater challenge compared to uphill propulsion. The presented prototype provides adaptable assistance when poling uphill and has significant braking effect downhills. The design has an important function in engaging more users and helping people with disabilities to become or stay active, which can potentially solve problems related to health and happiness. The electrical components can also be implemented and adapted for other sit-ski solutions, also as an accessory add-on. The presented engineering design shows a substantial benefit when both introducing paraplegic persons to skiing and enables slopes previously not accessible.

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