DESIGN OF EXPERIMENT FOR SPORTS EQUIPMENT - EXPERIMENTALLY MAPPING THE DESIGN SPACE FOR PARALYMPIC ALPINE OUTRIGGERS

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ABSTRACT
This article presents a design of an experiment for investigating the effect of changing the geometry of Paralympic alpine sit-ski poles/outriggers in the LW 10-12 class. An experiment design for mapping an individual athlete's performance parameters has been developed, with a resolution for finding the optimal outrigger geometry. By prototyping an adjustable experiment setup with implemented sensor systems, the performance increase can be analysed and implemented in new equipment. Results show that changing double poling geometry provides a substantial performance increase, regarding time and propulsive force.

Keywords: Early design phases, Design methods, User centred design, Paralympic alpine, Adaptive equipment

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1 INTRODUCTION AND BACKGROUND

In Paralympic research and development, equipment design has a substantial impact on performance (Mâsse, Lamontagne and O'riain, 1992; Rapp et al., 2016; Eikevåg et al., 2020). However, due to limited amount of research papers, design optimization is a challenging task depending on type of sports. Therefore, the design of experiment is a crucial element in engineering design to understand the design challenge, identify performance parameters, and implement results in engineering design for a particular case. There are also few manufacturers providing Paralympic sports equipment at a top level, and the equipment often has limited customizing options for use in experiments with athletes. Paralympic equipment is often designed on outdated research, or after well-established models and experiences from sports science based on fully functional athletes (Silberman et al., 2005; Shan, 2008; Iriberri et al., 2009; Burt, 2014). The lack of knowledge may cause some athletes to perform at a sub-optimal level, while others use customised equipment designed after their impairments providing a competitive advantage. A strong argument can be made that in competitive sports; equipment should not be the limiting factor. If athletes' individual performance parameters are identified, and equipment are customized accordingly, the competition would be fairer with a higher focus on the athletes. However, unknowns regarding movement and muscle activation are a design challenge when designing Paralympic sports equipment, as there are several different impairments, at different levels, within the same classes. Investigating impact of performance parameters on an individual level for Paralympic sports, in this case Paralympic alpine sit-skiing in the LW 10-12 class, could help athletes rise to a new level, and collect valuable data for manufacturers to be used in future designs. Without proper knowledge and with a lack of biomechanical models, heuristic testing of top-level athletes is a crucial part of engineering design at the highest level. New research is also supported by the sit-ski regulations as rules states that equipment can be customized and tailored per individual athlete ('WPAS Equipment Rules 2020/2021', 2020).

As there are many different variables to consider, breaking down the sports into sections is beneficial for analysis. We introduce Paralympic alpine sit-skiing as a two-stage process. First, the athlete double-poles to create acceleration. This stage usually last for approximately 15 meters but varies according to alpine disciplines. In the next stage, the athlete changes functionality of the poles called outriggers, by flipping down skies triggered by a mechanical mechanism. With the skies flipped down, the purpose of the outriggers are supporting the Paralympic athlete during the run (De Luigi, 2018).

This paper focuses on the first stage of alpine skiing in the LW 10-12 class, investigating the effect of changing the outrigger geometry for each individual athlete, in addition to a human centred design.

We present an experiment using modular poles and an improvised sit-ski with implemented sensor technology for evaluating athlete performance based on the dimensional change of the modular poles.

1.1 On Paralympic Alpine

Paralympic alpine skiing was developed as ex-servicemen with injuries returned from World War II in the late 1940's and wanted to return to their favourite sport. Paralympic alpine skiing is downhill skiing utilizing assisting equipment enabling the paraplegic users. Today it has developed to a competing sport, part of the winter Paralympics. In PyeongChang 2018, 114 Paralympic alpine athletes competed in five different disciplines ('WPSS Strategic Plan', 2020).

To ensure a fair and equal competition, Paralympic alpine skiing is divided into three groups of classes to classify the impairment and the degree of the impairment ('WPAS Classification rules and regulations', 2017):

- Sport classes LW 1-9 classifies the standing skiers that have leg or arm impairments.
- Sport classes LW 10-12 classifies the sit-skiers that have an impairment affecting their legs.
- Sport classes B1-3 classifies the skiers with vision impairments.

For athletes in LW 10-12 several suppliers make different sit-skies, e.g. Scarver (Tessier, France) (Figure 1), Bullet (Alois Praschberger, Austria) and Yetti High Performance Bullet (Rad Ventures, USA). Alpine outriggers are available through several suppliers and models, e.g. Tracer outriggers (Tessier, France) and HOC2 outrigger (HOC, USA), which has a fixed ski tip, and Superlite outriggers (Enabling technologies, USA) which is seen in Figure 1 and has a rotating ski that can be fixed in double poling position and released by pulling the string.

The different suppliers deliver different lengths of the outriggers from handle to ski as well as the length between handle and elbow support. Some models are fixed and can be made to measurement, and some come with adjustability. However, no adjustability of the angle of the outriggers is found at any of the suppliers.

Figure 1. State of the art Outriggers (Custom Titanium Outriggers, 2020) and sit-ski (Scarver, 2020)

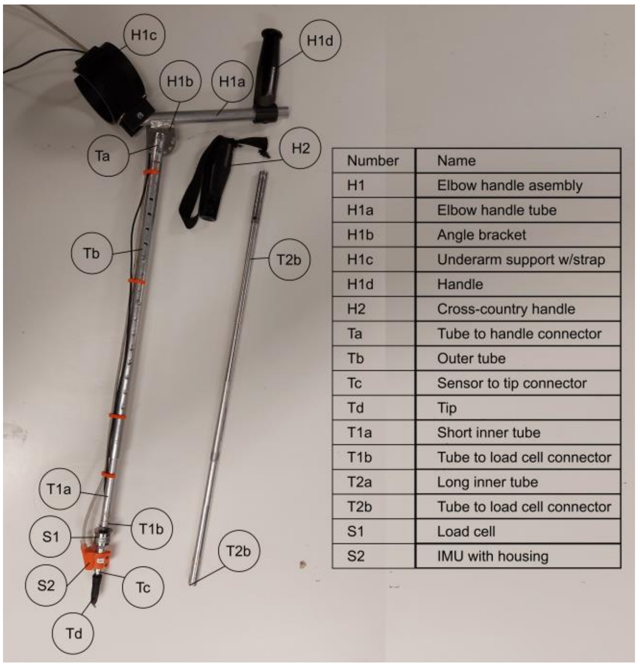
The WPAS Equipment Rules 2020/2021, (2020) have general rules for all adaptive equipment, equipment that are adapted to the special needs of Paralympic athletes, including the outriggers. However, as these rules are open, all adaptive equipment needs to be registered and approved (WPAS Adaptive Equipment Registration User Manual, 2019).

2 METHOD

The following section present an experiment and equipment for evaluating performance of different pole geometries at the first stage in the LW 10-12 classes. During the problem exploration phase of this project, multiple prototypes (Jensen, Elverum and Steinert, 2017) was made following wayfaring (Steinert and Leifer, 2012) to let the designers empathize with the users. One impression was that double-poling with the existing outriggers is very limiting in terms of power generation and range of motion.

2.1 Test equipment

To enable testing of Paralympic athletes, two pairs of modular poles (Figure 2) were created to enable data collection, while changing lengths and angles. They act as a product platform, utilising both scalability and modularization (Simpson, 2004). The poles are created fast, cheap, and robust, using available machines and consists mainly of aluminium tubing and connectors, polymer components, bolts, and nuts. The polymer components were created with a high amount of customisation and complexity at low cost using additive manufacturing (Deradjat and Minshall, 2017). Aluminium was chosen for its light weight, machineability and availability.



Number	Name
H1	Elbow handle asembly
H1a	Elbow handle tube
H1b	Angle bracket
H1c	Underarm support w/strap
H1d	Handle
H2	Cross-country handle
Ta	Tube to handle connector
Tb	Outer tube
Tc	Sensor to tip connector
Td	Tip
T1a	Short inner tube
T1b	Tube to load cell connector
T2a	Long inner tube
T2b	Tube to load cell connector
S1	Load cell
S2	IMU with housing

Figure 2. Parts of the developed force and angle measuring pole

To change the pole length, the inner tube can slide inside the outer tube and fastened using bolts. A sensor package, and tip, can be moved between poles. Use of load cells and inertial measurement units (IMU) has been done for analysing cross country skiing (Holmberg et al., 2004; Vähäsöyrinki et al., 2008; Stöggl and Holmberg, 2011). However, no found literature use force and angle measurements to focus on double poling of alpine sit-skiers.

The poles offer 11 different angles with 23 different lengths spaced 25 mm apart. Also, there is a set of cross-country handles. This provides a design space with 276 different configurations, with a benchmark at (15°, 843 mm) (Figure 3). The benchmark is close to what is being used today by Paralympic sit-skiers. The poles enable thorough testing of Paralympic athletes, identifying the close to optimal pole configuration per athlete. Changing the configurations is an easy procedure that require simple tools.

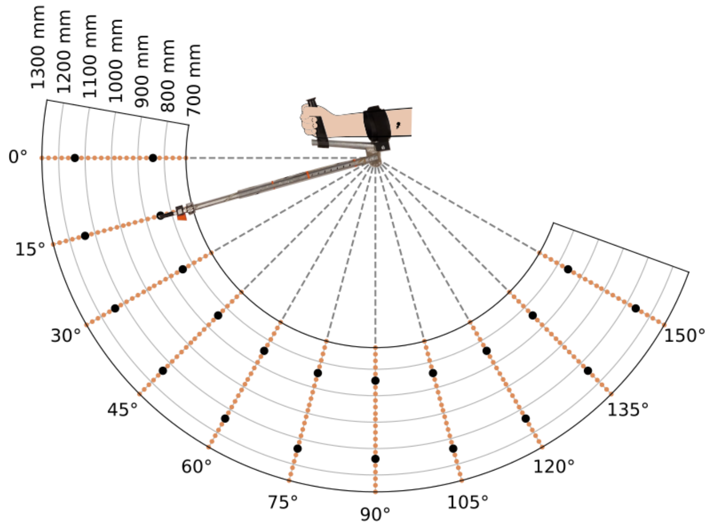


Figure 3. The design space of the modular poles. Small spots showing all configurations available, with a range of 0-150 degrees and 718-1264 mm length. Large spots showing the tested configurations at 843 mm and 1139 mm.

To test the effect of different pole configurations, a sit-ski on wheels was designed, enabling fast testing of poles (Jensen, Elverum and Steinert, 2017) and athletes when lacking snow. Many Paralympic sit-skiers use Scarver ('Scarver - TESSIER's ultimate sitski', 2020) and therefore the sit-ski was made with similar geometries to the Scarver sit-ski (Kennedy, Sobek and Kennedy, 2014).

A system for data collection was implemented to extract data from the equipment. The data includes force, time, and orientation for poles and sit-ski. With force and angle measurements, one can calculate double poling frequency and decomposed forces. Together with timing and video, the biomechanics can be analysed. The relative angle between the poles and terrain can be deduced from MPU6050s (InvenSense Inc., USA) on poles and sit-ski. To measure the force, in-line 2kN load cells from the 200 Series of Richmond Industries (Richmond Industries Ltd., UK) are connected to HX711 amplifiers (Avia Semiconductor, China). The sensors were placed as close to the end of the poles as possible to get exact data even if the pole would elastically bend during loading phases. The data from the poles are gathered using an Arduino Mega 2560 (Arduino, Italy), and an Arduino Nano (Arduino, Italy) for the sit-ski sensor. The sampling rate is 80Hz and limited by the amplifiers. The data was stored on SD cards.

2.2 Design of experiment

This section describes the setup and execution of the experiment (Fisher and Whitcomb, 1960; Anderson and Whitcomb, 2000; Antony, 2014). In each test, the athlete is performing double poling on a running track. The athlete is strapped into the sit-ski at the waist, the middle of the thighs and at the ankle, to disable leg movement. There are two different athletes in this experiment, described in Table 1, to increase the amount of data without excessive time consumption. Both athletes had no to little experience regarding double-poling.

Time consumption is a limiting factor for testing. Top athletes cannot afford to spend time on equipment testing that interrupt their training program, therefore the experiment is limited to one session. A good approach is validating the experiment with available personnel before introducing it to athletes. This paper focus on the experiment design. The recovery needed between each run, to avoid fatigue being a major factor affecting the results, limits the number of test runs in a session. Testing multiple configurations is prioritized over multiple datapoints per configuration to map the design space, albeit less accurate. Testing on flat ground lessens the physical stress between tests. Although a flat track differs from the slope in competitive racing, it provides a standardized surface, allowing easy-access testing. One may identify a region of interest, slimming the experiment volume for future slope tests, allowing sampling of multiple data points for each configuration. Even with the flaws mentioned, the experiment should be able to prove if the approach is viable for a competitionlike testing environment at a later stage and indicate whether one can expect significant improvements or not.

Table 1. Identification of the athletes regarding gender, age, height, mass, arm length and trunk length.

Athlete	Sex	Age [years]	Height [cm]	Mass [kg]	Arm length [cm]	Trunk length [cm]
1	M	24	176	79	74	49
2	F	24	164	58	69	44

A witty timing system (Microgate, Italy) containing photocells and reflectors was used to get the exact time at 5 m and 15 m. The track and the timing system can be seen in Figure 4. The checkpoint was set at 5 m to map the initial acceleration section (Bret et al., 2002; Coh and Tomazin, 2006). The total distance was set to 15 m as it corresponds with the distance to the first gate in Paralympic alpine skiing.

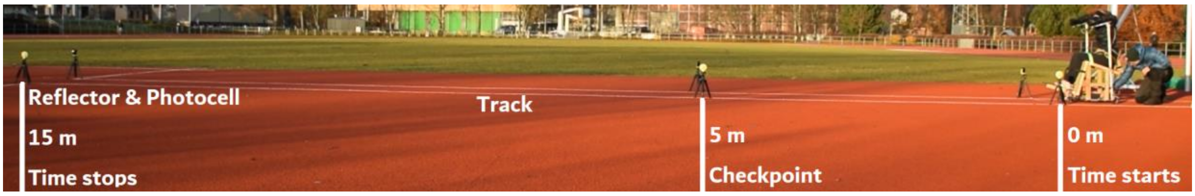


Figure 4. Overview of the test setup at running track. Total distance of 15 m, with witty timing system consisting of reflectors and photocells at start, finish, and a checkpoint at 5 m.

The athletes performed double poling at maximum effort, estimated to last ca. 15 sec each lap. In between there was a minimum of 3 minutes break per athlete to prevent fatigue. The breaktime was decided based on work done by Freitas de Salles et al., (2009), Faiss et al., (2015) and Børve et al., (2017). After each lap, the athlete was asked how he/she felt about the poles in terms of performance and feeling, on a scale of 1 to 5; 1 being terrible and 5 being fantastic (Passmore et al., 2002). The poles had two different lengths, 843 mm and 1139 mm, with 11 angles. There were also cross-country ski-pole handles for both lengths, totalling 24 configurations. The testing order of the configurations were randomised (Figure 5).

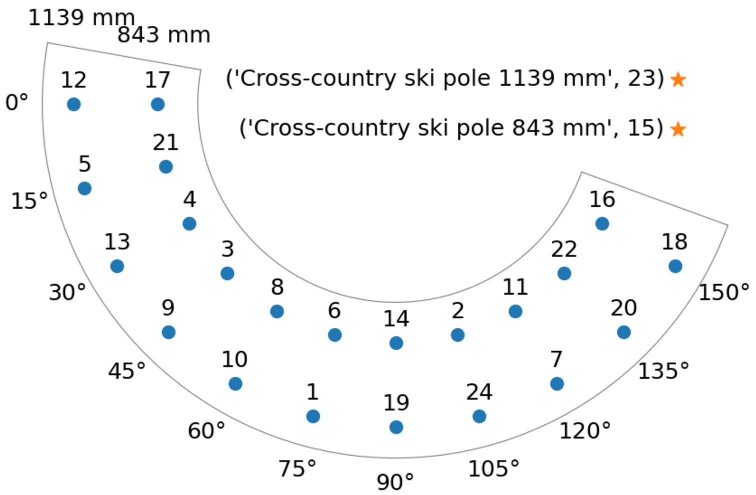


Figure 5. Each dot represents an angle and length for testing, stars represent cross-country ski poles. The accompanying numbers shows the test order.

3 RESULTS

The following section presents results from the tests. The first part will present results from the timing system and feedback from the athlete. The second presents data extracted from the adjustable poles.

3.1 Time measurement and athlete feedback

The time measurements of both athletes at 5 m and 15 m are presented in Figure 6 and Figure 7 respectively.

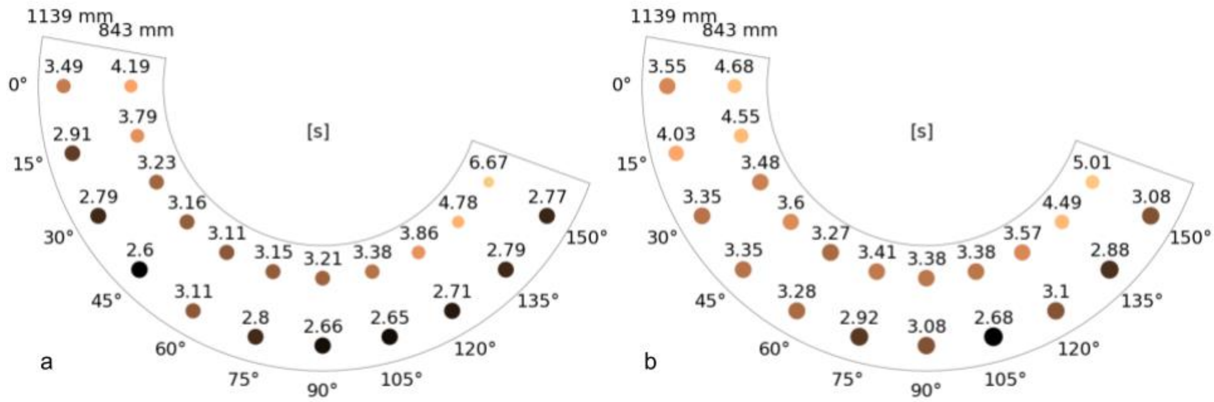


Figure 6. Time [s], at 5 m of a) athlete 1, b) athlete 2. The darker and larger dots represent faster times.

Using cross-country ski poles at 843 mm, athlete 1 used 3.55 s to the 5 m mark, whilst athlete 2 used 3.7s. With cross-country ski poles at 1139 mm, athlete 1 used 2.69 s to the 5 m mark and athlete 2 used 2.67 s. At the 5 m mark, the best result of athlete 1 is at (45°, 1139 mm), however, the most consistent well performing range can be found from 90 to 120 degrees with 1139 mm length. Athlete 2 has two points that stand out at the best, (105°, 1139 mm) and 1139 mm cross-country ski poles.

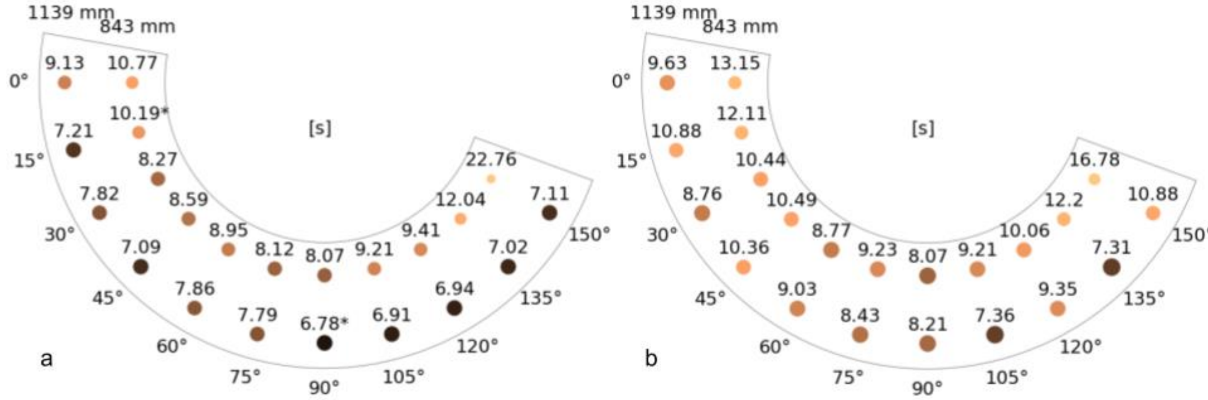


Figure 7. Time, [s], at 15 m of a) athlete 1, b) athlete 2. The darker and larger dots represent faster times.

Using cross-country ski poles at 843 mm, athlete 1 used 8.17 s to 15 m mark, whilst athlete 2 used 8.8 s. With cross-country ski poles at 1139 mm, athlete 1 used 6.54 s to the 15 m mark and athlete 2 used 6.53 s. At 15 m, both athletes performed best with 1139 mm cross-country ski poles. For athlete 1, the best performing range is 90 to 120 degrees with 1139 mm length, the same as at 5m. Athlete 2 has more variability in the results, but there are two configurations that perform notably better than the rest, (105°, 1139 mm) and (135°, 1139 mm).

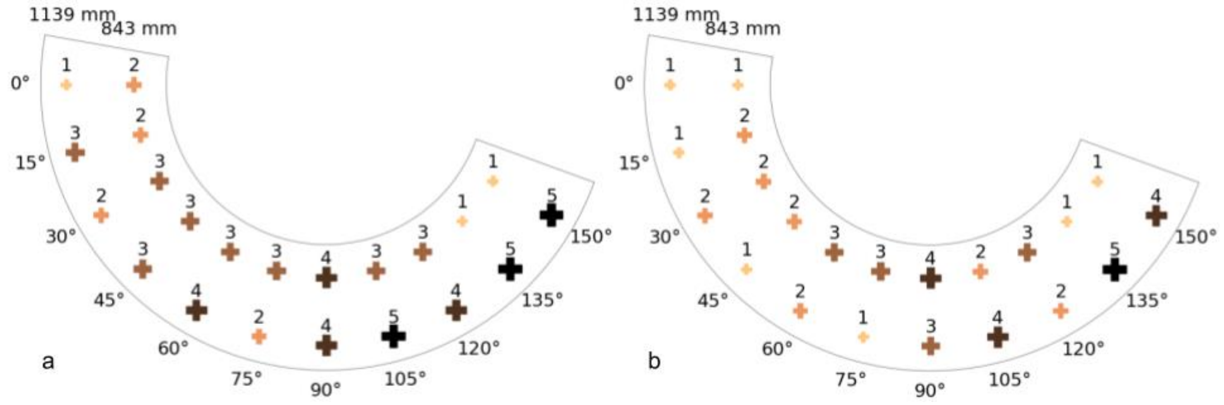


Figure 8. Reported feeling of a) athlete 1, b) athlete 2. 1 (Terrible) - 5 (Fantastic). The darker and larger crosses represent better feeling.

Figure 8 shows the athletes' feedback on the configurations. Both athletes graded the 1139 mm cross-country ski poles and (135°, 1139 mm)-configuration a 5, and the 843 mm cross-country ski poles a 4. The best reported range was from 90 to 150 degrees with 1139 mm length for both athletes.

3.2 Frequency and force measurements

The double poling frequency is calculated from the pole forces measured by the load cell. A fast Fourier transform is applied, and the most dominant frequency is reported for each run in Figure 9. The results show no immediate difference in frequency for long and short poles. However, we observe that the elbow supported poles with the best performing time for each athlete, (90°, 1139 mm) and (135°, 1139 mm), had a double poling frequency of 1.15Hz.

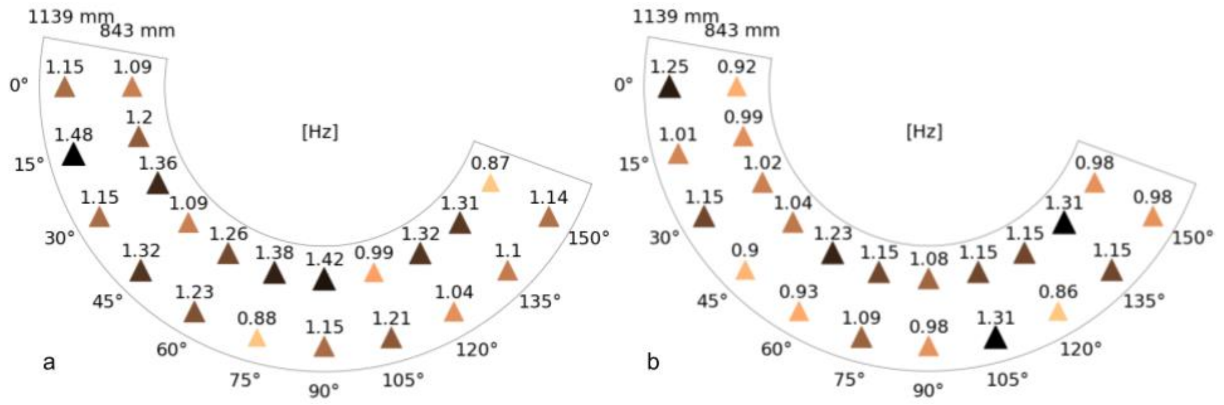


Figure 9. Double poling frequency [Hz] of the run for a) athlete 1, b) athlete 2. The darker and larger triangles represent higher frequencies.

The frequency for the 1139 mm cross-country ski poles was 1.09 Hz for athlete 1 and 1.23 Hz for athlete 2. For the 843 mm cross country ski poles, the frequency was 1.31 Hz for athlete 1 and 1.2 Hz for athlete 2. Force recorded from the load cell on the right pole was decomposed in two components. One in the sit-ski direction i.e., the propulsive force and one force normal to the ground. Figure 10 shows the benchmark configuration for athlete 1 and the best performing configuration is shown in Figure 11. The observed propulsive force in the benchmark configuration is smaller than the normal force but is fairly consistent over the run.

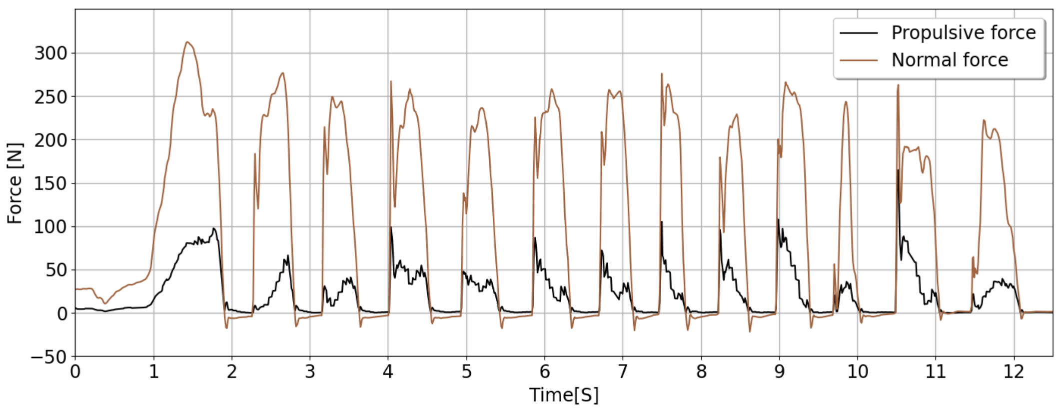


Figure 10. Athlete 1 (15°, 843 mm) benchmark position. Normal force and propulsive force.

For the best performing configuration, the component in sit-ski direction is highest in the first strokes, but the maximum force normal to the ground is more constant. The average force in velocity direction is 21N for the benchmark position.

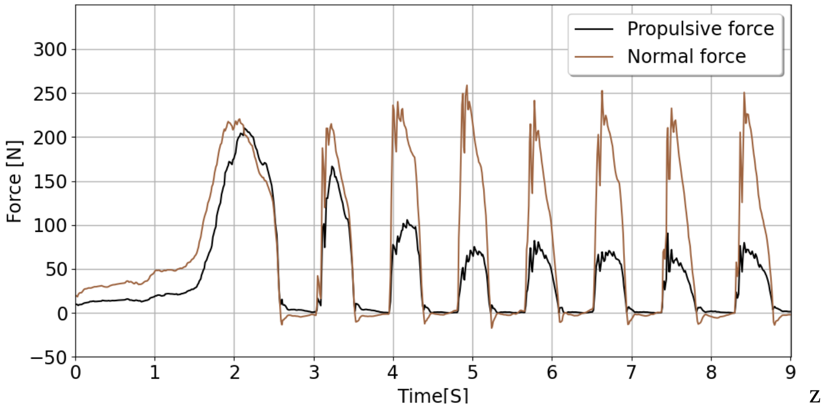


Figure 11. Athlete 1 (90°, 1139 mm) best performing elbow handle configuration. Normal force and propulsive force.

The propulsive force is observed to be greater and the normal force slightly smaller in the best performing configuration. The differences are most notable in the first couple of strokes. The average force in velocity direction is 41N for the best performing elbow handle configuration.

4 DISCUSSION

The design of experiment is evaluated through the results. A high, but reasonable, difference between best and worst result may indicate the experiment's ability to uncover an athlete's optimal pole configuration. The elbow supported poles' best configuration performed better than the benchmark. In this preliminary experiment, the improvements were 33% and 40% over 15 m for athlete 1 and 2 respectively. Both athletes performed best on 15 m with cross-country ski poles length of 1139 mm. Compared to the benchmark configuration, athlete 1 and 2 improved performance by 36% and 46%. Better performance with cross-country poles is expected as these are similar to poles used in Paralympic cross-country skiing (Rapp et al., 2016).

When comparing the power curves showing the propulsive force and the force normal to ground (Figure 10) and (Figure 11), changing the configuration had a huge impact on the propulsive force. Athlete 1 increased the peak propulsive force of the sit-ski by 114% during the first stroke, when comparing the benchmark position and best performing elbow supported poles. The following strokes also provided a significant increase in power, and the average force in velocity direction was increased by 95.2%.

In alpine skiing the power produced in the first couple of strokes are crucial as the speed generated will potentially benefit the whole run. The sensor setup used in this setup, can provide data for analysing propulsion force, traction, and detect instability used both for analysing new equipment and technique.

There are multiple uncertainties within the results. As the initial design space is quite large, each pole configuration was only tested once, trading better accuracy for complete mapping in the available time

frame. Another uncertainty comes from the athletes getting better at double poling. As they had little to no prior experience with this activity, it is expected that they gain better technique during the experiment. Performance increase is shown to happen quickly in people with little to no experience with an activity (Seibel, 1963). Each athlete did 32 runs, including the runs that failed due to mechanical, electronic or personal reasons. It is believed that the additional runs did not impact the results much, as the athletes reported no increase in perceived fatigue.
The results present a new set of challenges. 1) they indicate that the double poling configuration should be a different configuration to the one the current poles offer. This optimal configuration can be found through further experiments. From the results it is possible to identify a smaller area within the design space suited for further testing. 2) if the current poles available represent a compromise between double poling and downhill skiing, the skiing configuration may also be optimised. 3) if the optimal double poling configuration is different from the optimal skiing configuration, that presents a design challenge to manufacture the solution within the equipment rules.
The results from this experiment are not directly transferrable to other athletes. However, the experiment may help other athletes find an area in the design space improving their performance. Within this area, one can test with higher resolution. The better performing areas in our results may indicate areas of interest for other athletes.
As the general Paralympic skiing rules allows equipment modifications, with a design of experiment, other Paralympic athletes not connected with scientific research may now optimize their equipment by following the methodology that could be presented in revised regulations. By further enhancing the design of experiment methodology presented in this article, the method may also assist athletes in different sports as previously presented by Eikevåg et al., (2020) and Severin et al., (2021).
With these poles it is possible to determine an athlete's optimal configuration for double poling. As Paralympic athletes have varying degrees of impairment this configuration may be different from athlete to athlete, highlighting the need for individually customised equipment.
The design community may benefit from the approach used in the presented work. It can be used in other engineering design task where the product has multiple functionalities and when there is a lack of knowledge. By focusing on a functionality that is not understood one can gain valuable knowledge early in the design process instead of spending time on designing the final product without the desired knowledge. With individually optimized equipment, each athlete gets closer to fulfil their maximum performance potential. The implications may be a levelling of the playing field as the athletes do not have to force into standardized components.

5 CONCLUSION

In this article, an experiment was conducted to test different angles and lengths of outriggers for double poling in Paralympic alpine sit-skiing. A pair of outriggers or better named; poles, as they only focus on double poling, is developed and includes sensors for force and angle measurements. The poles enable testing with the athlete to find their individually optimized pole configuration.
Through the preliminary experiment in this article, the design space has been roughly mapped in terms of performance for two subjects. Each map indicates an individual area that should be tested further by Paralympic sit-skiers during alpine skiing. The results suggest that by introducing different lengths of the poles and angles of the elbow handles, double poling performance can be improved. From the benchmark-configuration to the best performing configuration, both subjects had an increase in performance. Thus, confirming the design of experiment's suitability to determine the design conditions for equipment improvement per individual athlete.

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