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Human Geometries as Key Starting Point in Sports Performance - Designing Equipment for Individual Performance in Paralympic Sit-Ski

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Abstract

This article investigates human geometry in design, allowing exploration of unknown geometries in Paralympic sports equipment. By creating a configuration map exploring the solution-space, optimal sit-ski seating positions–in the sense of performance and ergonomics–can efficiently be found for individual athletes. A physical prototype was developed, and an experiment was designed to identify changes in performance due to different geometries. The design method and application make it possible to translate critical angles onto geometries, and test individuals for optimal work ergonomics.

Keywords: prototyping, user-centred design, design methods, paralympic cross-country skiing, ergonomics

1. Introduction

The human aspect plays a crucial role in design research (Wilkinson and De Angeli, 2014). In sports adjusting equipment according to the human geometries have provided a substantial performance increase (Iriberri, Muriel and Larrazabal, 2008; Shan, 2008; Burt, 2014), and particularly in Paralympic sports (Mâsse, Lamontagne and O'Riain, 1992; Rapp et al., 2016; Eikevåg et al., 2020; Severin et al., 2021; Silseth et al., 2021). When comparing the geometry of an athlete's body and that of the equipment, a mismatch may arise, resulting in suboptimal equipment. Also, the sports equipment used by fully functional athletes may cause design fixation when developing Paralympic sports equipment at a preliminary state. Therefore, the specific design question discussed in this paper is how to properly investigate what is the right fit in terms of work ergonomics when working with Paralympic athletes at the highest level. Early-stage prototypes can be created with infinite degrees of freedom in the relevant design space (Silseth et al., 2021) (i.e., the space describing the limits of the prototype) by first looking at the fundamentals in human geometries. So, using known design methodologies (Steinert and Leifer, 2012), we propose a new methodology for developing and evaluating user-adapted sports equipment–in our case for Paralympic sit-ski. The key elements of the methodology are creating and mapping out a design space limited by the general human geometry. Then create a physical prototype covering most of the design space to allow for as much freedom as possible when exploring the ergonomic possibilities. Combining this exploration process with an experiment designed to test and evaluate the performance of each chosen ergonomic configuration will benefit the design community as it suggests a "human-to-product" path that may be used when designing user-adapted sports equipment.

In sports science, measuring performance can be challenging caused by multiple factors. The overall goal in a Paralympic cross-country skiing race is to reach the finish line first, so all factors contributing to achieving this would be considered performance-enhancing. Measuring O2 uptake, blood lactate, heart rate (HR), and propulsion force as performance associated parameters are among techniques being used (Jacobs, 1986; Arts and Kuipers, 1994; Lucía et al., 2000; Sletten et al., 2021). In an early-stage iterative process, we explore the effect of HR as a performance parameter in combination with a human-centered design. By creating a new design method, eliciting unknown unknowns (Jensen, Elverum and Steinert, 2017) may contribute to an additional performance increase, as discovered throughout the process.

1.1. On Paralympic cross-country skiing

Cross-country skiing was introduced in the Paralympics Winter Games in 1976 and has been included ever since. Male and female athletes compete in team relays, sprints, short, medium, and long-distance ranging from 1 km to 30 km. In addition, athletes can choose to use a classic technique or a free technique while competing. Within cross-country skiing, there are also several different classes, all depending on the limitations and impairment of the athlete. The three categories are sports classes LW 2-9, which focuses on standing skiers; sports classes LW 10-12, which focuses on sit skiers; and sports classes B 1-3, which focuses on vision impairment (Nordic Skiing - Rules and Documents, 2021). This paper focuses on sports classes LW 10-12. Special rules for this class are that the buttock must be secured onto a seat during the race, and the maximum height between this contact point and the skis cannot be higher than 40 cm. All equipment that increases the athlete's performance except the design and seating position is restricted.

Today's sit-skis are very simple and have minimal adjustment possibilities (see Figure 1). One can choose between sitting with the legs forward or sitting on the knees. The angle between the sit-ski and the legs is not adjustable for the latter position. It is normal to only be able to change the seat's height and change the leg supports' location. An example of a sit-ski being used today is the Skeno Power Piggkjelke.

Figure 1. A sit-ski currently used by athletes

2. Method

To investigate the design problem outlined, a predominantly quantitative design-space was introduced. Thus, we could visualize and organize how an individual human geometry can be fitted into different positions on a sit-ski. In addition, an experiment was designed to evaluate and investigate the equipment performance, and four unique geometries were tested.

2.1. Designing testing equipment in a user-centered design space

By looking at the hip, knee, and leg as three separate coordinates, a quantitative design space was defined above the sit-ski, limited by the biomechanical limits of the test subject. As seen in Figure 2, a prototype was built, allowing the three joints to move as freely as practically possible. The prototype consisted of an aluminum frame mounted on roller skis. Paddings for the knee and leg were mounted on adjustable beams. A seat was mounted in the same way as the knee and leg paddings, but with the added possibility of switching between a wide seat and a bicycle seat to achieve more design freedom. Roller skis (with two-way bearings, making the skis able to roll both ways) were added to the bottom of the frame for later test purposes.

Figure 2. The prototype (Left with a bicycle seat, right with a wide seat)

A mapping of the possible geometries and configurations (Figure 3) creates a clear view of the possibilities the prototype could provide for a specific athlete. Because the hip, knees, and legs are not biomechanically able to move freely inside a space independent of each other, an adjustable down-scaled version of a human test subject was made and placed around on the configuration map to explore possible joint coordinates. Thus, the sketch works as a prototype itself as it helps to uncover more possibilities, not apparent at first in the physical prototype (Jensen, Elverum and Steinert, 2017).

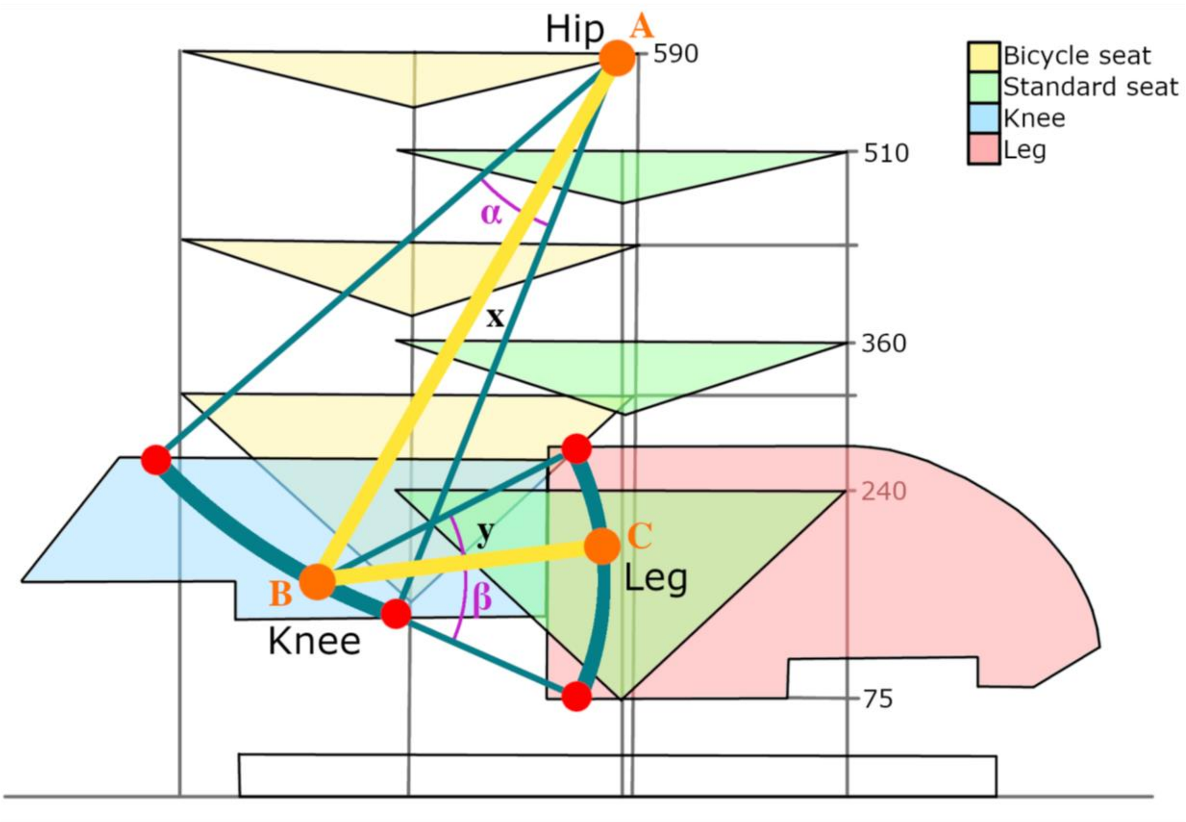

Figure 3. The configuration map. Shows areas where the three joints can be placed. Hip can be placed inside the bicycle seat and standard seat areas. Points A, B, and C represent the hip, knee, and leg placement, respectively. Length x and y represent respectively thigh-length and leg-length. Dimensions are measured in millimeters

The length of the thigh x and the leg y varies individually. Locking the hip into e.g. point A, limits the possibilities for placing the knee to the range α. If the knee is, for example, then placed at point B, the leg is consequently limited to the range β, which finally allows us to place the leg in point C. The lengths x and y vary from person to person, suggesting that different geometries must be possible for different test subjects. This fact is important to stress as it means that an individual's physiology is crucial in deciding what seating positions are possible, which again supports the need for a prototype that allows the three joints' free movement inside the chosen design space. After exploring several different geometries, four positionswere tested in a quantitative experiment to validate our design method. The top of the configuration map exceeds the regulations; however, this area still needs to be explored to gather knowledge about the limitations, and thus potentially lead to a performance increase.

2.2. Experiment design

Given that we are designing equipment for Paralympic cross-country skiing, a realistic test setup would naturally include a snow test using skis on a Paralympic competition track. Snow would include unknown factors such as varying friction between skis and snow, skidding, and others. However, we are comparing geometries and looking into how they isolated will affect an athlete's overall performance and therefore used roller skis on asphalt, with fewer unknowns.

The track shown in Figure 4 starts with a slight uphill for about 150 m. This was followed by a right turn and a steep downhill past the 200 meter mark. The track then curves left into a steep uphill after around 250 m. A sharp left turn occurs right before the 300 meter mark, followed by a slight downhill leading back to the starting point. The length is approximately 500 m and has a total elevation-difference of approximately 4 m. The uphill curving to the left is classified as a B-hill, and also fulfills the criteria of having an uphill after the steep downhill (*Nordic Skiing - Rules and Documents*, 2021). The track is located outside NTNU in Trondheim, Norway.

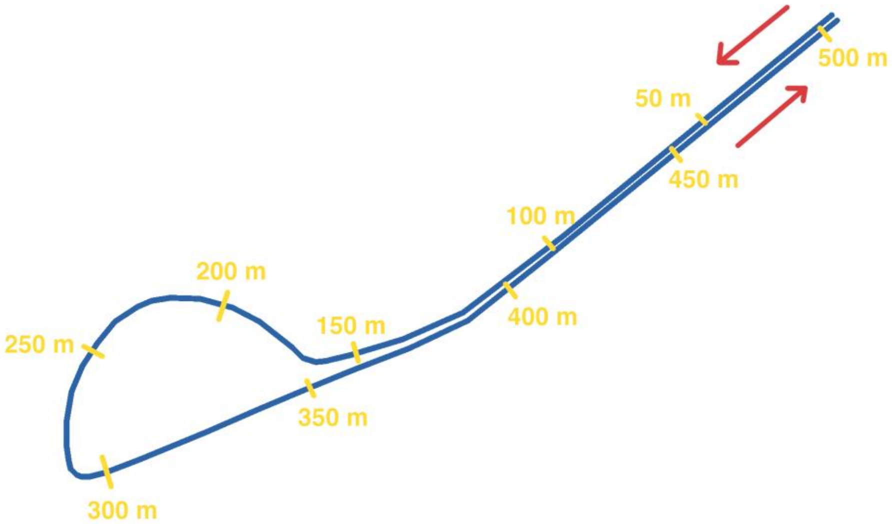

Figure 4. Map showing the track profile. Arrows indicate the direction and the length is marked every 50 m

Time consumption is a limiting factor when working with top level athletes as missmatches between their training program and testing is undesirable. Therefore methodology and prototype iterations were developed using fully funtional athletes, and the experiment design limited to a single day. Four positions were tested (Figure 5) to investigate the extremes in the configuration map. The prototype was then adjusted to the first test geometry (i.e., position 2). The athlete entered the prototype, strapping the hip and knees tightly. Next, the ski poles were adjusted to match the height of the shoulder for each position. The 185 cm tall male athlete weighed 79 kg, had 49 cm thigh length (Length x in Figure 3) and 25 cm calf length (Length y in Figure 3). The athlete did not have any experience sit-ski-double-poling beforehand and was tested as a trial-run to investigate flaws in the experiment design.

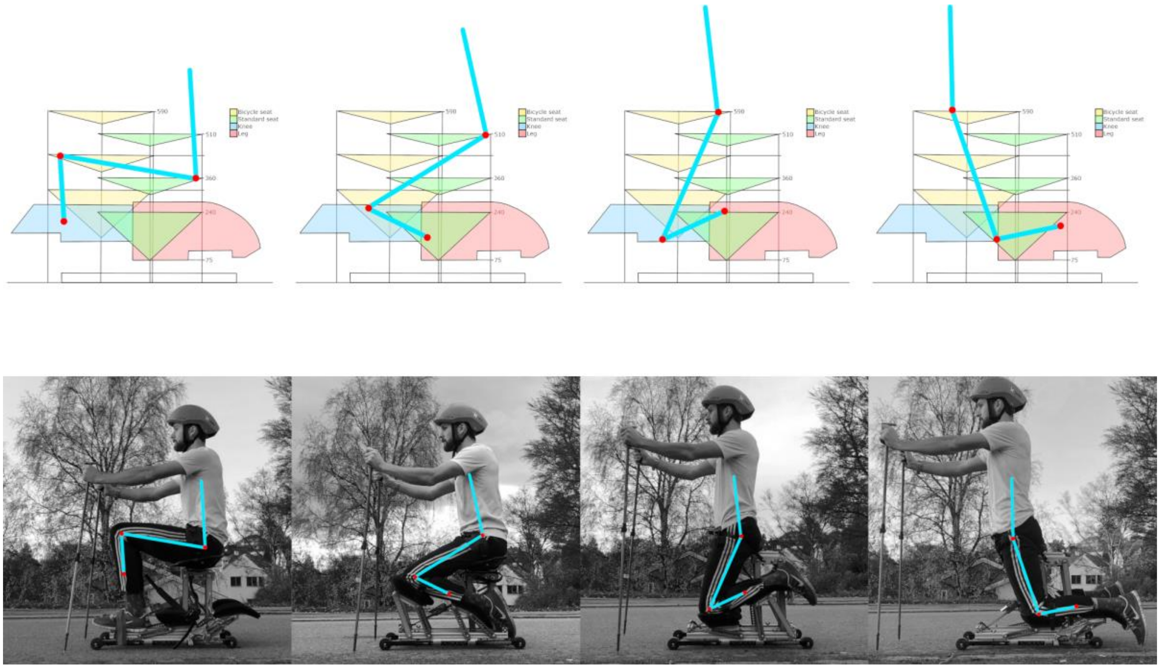

Figure 5. The four experiment positions, both from the design equipment and on the prototype. From left to right: Position 1, 2, 3 and 4

To investigate the effect of the different positions, the athlete performed the track at a constant speed, making physiology data the variable performance indicator. First, test rounds were conducted to validate aspects of the experiment, such as that we were able to maintain a constant guiding speed. A standalone tracking system consisting of an iPhone 8 supported by both GPS, GLONASS, and Galileo was used to validate constant walking speed when walking through the track. In the downhill section of the track, the athlete was held back in constant speed for safety reasons. Three successful test-rounds were done for each position with a 5-minute break (Freitas de Salles et al., 2009), with the exception of position 4. Breaks between the different setups were longer due to the time it took to adjust the prototype.

In order to measure performance in the following experiment, we used easily accessible wearables to obtain early-stage data. We wanted to measure HR and used the Garmin Fenix 6 connected to a Garmin HRM-Pro belt. Garmin allowed us to extract time, position, distance traveled, HR, altitude, speed, and other parameters in the same system with a single timestamp. When measuring position, we configured the Garmin watch to combine GPS and GLONASS to achieve high positional accuracy (Hofmann-Wellenhof, Lichtenegger and Wasle, 2007), and measurements were taken at a frequency of 1 Hz. A study comparing different GPS sports watches (Johansson et al., 2020) concluded that all the watches tested (including Garmin Fenix 3) were feasible for measuring the position. However, the watches in the experiment only used GPS, and not GPS combined with GLONASS. According to Szot et al. (2021) and Zhang et al. (2014), the combination of several GNSS systems (such as GLONASS, GPS, and Galileo) will increase the accuracy substantially.

Several studies have shown that when measuring HR, using a HR monitor based on ECG technology is preferred over the internal PPG (Castaneda et al., 2018) measurement method located in the clock itself (Ge et al., 2016; Gillinov et al., 2017; Etiwy et al., 2019; Baek, Ha and Park, 2021). HR was measured using the Garmin HRM-Pro belt, and a similar setup has earlier proven to be highly accurate (Gilgen-Ammann et al., 2021).

Combining the fact that the positioning system is relatively accurate, that it is possible to obtain HR measurements, and that all data (i.e., position, distance traveled, and HR) is extracted at the same timestamp makes this measuring system a suitable candidate for easy measuring sports equipment performance.

The data was obtained by exporting it from the Garmin Connect software in a .tcx raw data format, converting it into a .csv-file for later being processed in a python-code, and eventually creating a graphical visualization for further analysis.

3. Results

The experiment was conducted in October 2021. Position 2 was first tested four times where the first test was conducted as a control test and warmup. Secondly, position 3 was also tested four times (the first test failed because of mistakes during the prototype setup). Position 4 was tested one time but failed as it was too heavy and painful for the athlete to complete. Lastly, position 1 was tested three times. The results from the experiment are shown in Table 1 and Figure 6.

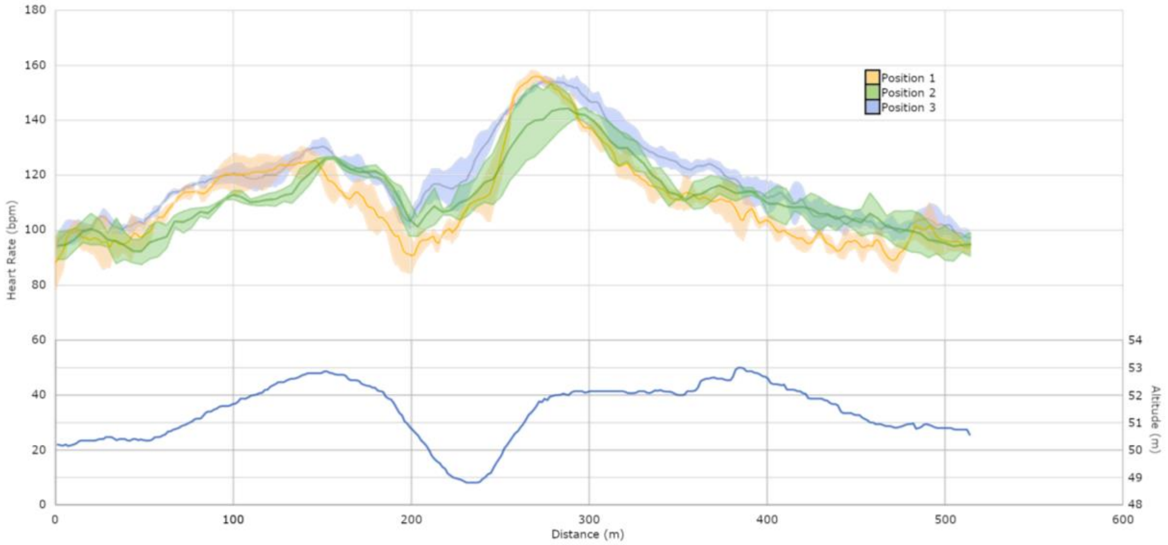

Figure 6. Graph showing mean HR values for different positions with standard deviation. The appropriate altitude curve is plotted underneath

The results from the graph show that the mean HR values in position 2 are lowest in the uphill section. However, the standard deviation overlaps with the ones in the two other positions in most parts. Position 2 also gives the lowest mean HR in the first section of the track, while the two other positions are quite equal in this part. The HR in position 1 increases faster in the uphill than the two other positions but is lower in the track's steepest declining section. This position is also the one giving the lowest HR in the last 150 meters of the track.

Table 1. Position 1, 2, and 3 with average duration, average max HR uphill, average max HR flat, average HR with their respective standard deviations. Average max HR flat and average max HR uphill represents the first and second peak in Figure 6 respectively

	Avg. Duration	Avg. Max HR, Uphill	Avg. Max HR, Flat	Avg. HR
Position 1	05:57	157,3 ± 1,2	126,7 ± 3,8	112,3 ± 2,3
Position 2	06:00,5	148,0 ± 5,3	127,3 ± 0,6	113,0 ± 1,7
Position 3	05:52,4	155,7 ± 1,5	130,7 ± 2,9	118,3 ± 0,6

Looking at the maximum values in Table 1, one can observe that the highest overall average HR arises from position 3. The two positions giving the highest maximum HR values occurs in position 1 and 3. Other qualitative comments from the athlete were that position 3 felt more demanding than position 2 uphill but better on the flat section of the track. Position 1 also felt more demanding than position 2 and 3 in general.

4. Discussion

Our method focuses on a human-centered design by utilizing the entire design space available, allowing individuals to test all different geometries that are biomechanically possible effectively. Furthermore, by utilizing the configuration map, one can investigate geometries for unique athletes without their presence. As the x and y variables vary individually, the method allows comparing angles, geometries, and center of gravity from one athlete to another by re-scaling these variables. The configuration map, along with the adjustable prototype, allows athletes to test all geometries effectively to optimize ergonomics, functions, injury prevention, and performance.

As professional paralympic athletes have strict training programs, the prototype and design of experiment should be developed before being presented to the Paralympic athletes. When using a non-impaired athlete and only measuring HR differences with constant speed over a short track, the experiment shows differences between seating positions. Prior to professional Paralympic athlete testing additional explorations, using human centred design, of individual user needs (e.g., support and strapping) are nesseasary to investigate the full individual athlete potential.

The HR measured from the different positions acted similarly to the track; however, variations and deviations can be observed. These differences might be caused by one geometry being more efficient than the other. For example, the mean HR for position 2 is lower than the other positions both in uphill and the first part of the track. The difference in HR for the different positions seems promising concerning performance, although it is uncertain since this is the first geometry tested, and the athlete's fatigue may have an effect.

At particular parts of the slopes during position testing, outliers might be caused by irregularities in the GPS+GLONASS system, resulting in a shift of the HR plots. Additional tests would most likely improve the accuracy of the results, making the positions more comparable. Fatigue of the athlete may also have affected the results, together with other uncertainties, such as interference causing the speed to vary. Finally, it is uncertain which effect the temperature differences throughout the day had for the HR, as we use it as a performance parameter. However, when analyzing the data, a clear difference can be noted between the different positions tested.

5. Conclusion

In this paper, a configuration map has been introduced to open up more possibilities in designing Paralympic sports equipment. We have broken down human geometry to an absolute number to extract a full customized geometric model, providing full control over the solution space. By breaking this model into scalable angles, we can compare different individuals and look at similarities regarding performance and ergonomics. By investigating the configuration map and then designing an experiment, the presented design method may assist designers in developing Paralympic cross-country skiing equipment for all athletes with all different shapes and sizes.

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