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Investigating the Effect of Sitting Position on Upper Body Range of Motion in Cross-Country Sit Skiing

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Abstract: In addition to effective training and optimization of physiological performance parameters, selecting the appropriate sports equipment is key to achieving ideal athletic performance. For Paralympic cross-country sit skiing athletes, this means that the sledge must be tailored to the individual needs of each athlete. An efficient sitting position and an individual sled design tailored to the athlete's impairment are crucial for the success of para-athletes. However, there is a lack of studies examining the effects of different sitting positions on sledging performance. In this study, a kinematic analysis of three representative positions was performed: knee high (KH), knee low (KL) and neutral (NT). The aim of the analysis was to identify differences in upper body kinematics among six athletes.The results indicate that the subjects had a greater range of motion in the KL position, which allowed for better force transfer onto the poles and thus resulted in significantly improved poling force and thus better forward drive. In contrast, the KH position exhibited a more restricted range of motion in the upper body, which could limit force transfer and their performance. In summary, the findings suggest that the KL position maximizes the upper body range of motion and overall efficiency in poling. This is significant for the selection of the individual sledge position and for fair classification in the sport

Keywords: XCSS, kinematics, biomechanics, acceleration data, IMU, range of motion, sledge.

1 Introduction

Paralympic cross-country skiing (XCSS) has been an official sport of the Paralympic Games since 1976, providing individuals with physical disabilities the opportunity to engage in a highly competitive and physically demanding activity. The sport has seen significant increase in participation over the years; for example, a total of 170 athletes are set to compete in the upcoming 2026 Paralympic Winter Games in Milan, representing a 20% increase compared to the previous Games in Beijing[1,2,3].

To ensure fair competition, athletes are classified according to their functional capabilities following the classification system established by the International Paralympic Committee. This system divides athletes into five classes based on their level of impairment: LW10 athletes have significant lower limb impairments and compete in a seated position with limited trunk control, while LW10.5 athletes exhibit slightly less severe impairments but still compete from a seated posture with greater trunk control. In contrast, LW11 athletes have upper limb impairments or moderate lower limb impairments and may compete either standing or seated. LW11.5 athletes possess better trunk control than those in LW11, allowing for greater stability during competition. Finally, LW12 athletes demonstrate full trunk control, enabling a wider range of motion (ROM) and a more effective sitting posture.[4]

The key equipment piece used in XCSS is a sledge called the sit-ski, which allows athletes to use solely their upper body and core muscles for propulsion and control of movement. Competitors propel themselves using two poles in a manner akin to the double poling technique employed by standing skiers, involving synchronized and symmetrical pole planting in the snow.[5]

In addition to effective training and optimizing physiological performance parameters, selecting suitable equipment is essential for achieving success in this sport. For XCSS athletes, customizing the sled to accommodate their individual impairment is essential for fair competition. Therefore, this study aims to investigate and analyze various sitting positions in XCSS to understand their effects on performance and overall athlete experience. This paper will focus on a kinematic

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analysis of the upper body during three representative sitting positions, addressing the question: How does the sitting position affect the ROM and stability of the upper body while sit-skiing?

2 Materials and Methods

2.1 Participant

Six able-bodied athletes (age: 25.17 ± 4.84 years; height: 181.17 ± 2.98 cm; weight: 74.67 ± 8.55 kg; 5:1 m:f) experienced in the double poling technique participated in the study. Participants were informed in advance about the study's protocol and the measurement tools, and had the option to withdraw from the measurements at any time. They also provided written informed consent. The study received approval from the Ethics Committee of Albert-Ludwigs-University of Freiburg (Application no. EK-Freiburg: 23-1343-S2).

2.2 Experimental design and protocol

All tests were performed on a treadmill (Motek Medical, Amsterdam, Netherlands) equipped with a wheel-based adjustable sled. Three representative sitting positions were tested: knee-high (KH), neutral (NT), and knee-low (KL), following the classifications outlined in the Para Nordic guidelines for sit skiing [4]. To standardize these positions, the tilt of the sitting platform was adjusted with a goniometer to angles of -10° (KH), 0° (NT), and +15° (KL) for each respective condition (see Figure 1).

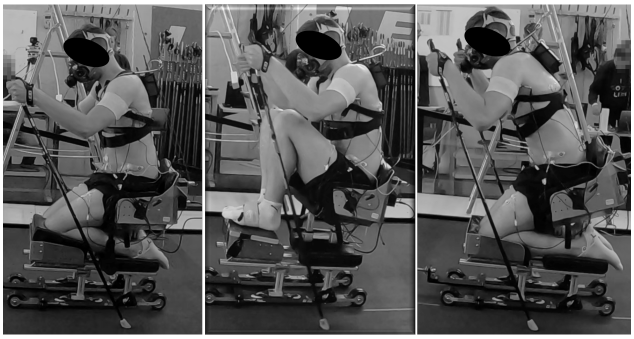

Fig. 1: The three representative sitting positions: neutral (NT), knee high (KH) and knee low (KL).

Participants were tested in all sitting positions while employing the double poling technique in a randomized order. The testing protocol comprised both a flat condition and an uphill condition. The flat condition was executed at a 1% incline to simulate air resistance, thereby reflecting the increased energy expenditure associated with outdoor performance. Each sitting position was tested for four minutes. Participants were instructed to select a comfortable speed that they could maintain for both the flat and uphill conditions. To ensure consistency in intensity across all participants, they were asked to choose a velocity that corresponded to a rating of 12 on the Borg Rating of Perceived Exertion (RPE) scale. The speed was determined during the warm-up while using the NT sitting position. All positions were assessed with a ten-minute rest period between each condition. The complete protocol is illustrated in Figure 2.

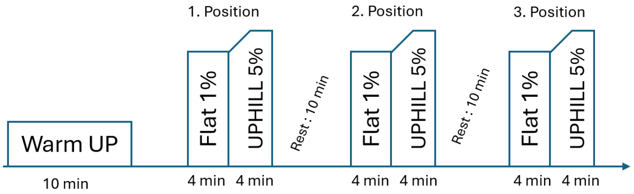

Fig. 2: The procedure was performed by athletes.

2.3 Measurements

Acceleration data were recorded using four 3-axis accelerometers (Shimmer3 IMU units, Dublin, Ireland) positioned along the back from the pelvis to the head at a sampling frequency of 128 Hz. The IMUs were arranged to maintain equal distances between each other and aligned in a straight line. Additionally, the IMUs were secured with straps to ensure they did not slip during dynamic movements. The data were collected using ConsensysPRO software and temporally synchronized, then transmitted to a laptop for subsequent analysis.The placement of the four IMUs is shown in Figure 3.

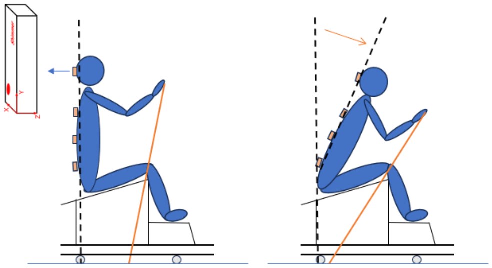

Fig. 3: Positioning of the individual IMUs.

In addition to recording acceleration data, pole forces were simultaneously measured using the Sessantaquattro wireless system from OT Bioelettronica S.r.l. (Turin, Italy) with a sampling frequency of 2000 Hz. The data was transmitted to a laptop for subsequent analysis. A force sensor (Type:

KD40S, Manufacturer: HKM-Messtechnik GmbH, Freiburg, Germany) was attached to the ski pole to detect contact with the ground.

2.4 Data processing and statistical analyses

The acceleration data from the four IMUs were processed using a second-order low-pass filter with a cut-off frequency of 6 Hz to achieve a clear and consistent activity pattern while minimizing disruptive noise. Additionally, a moving average filter was applied to the acceleration data to enhance pattern recognition throughout the signal. For the force data, a fourth-order low-pass filter with a cut-off frequency of 30 Hz was utilized to ensure a clear and uniform signal while reducing interfering noise. The acceleration data and the force signals, which were recorded at different sampling rates and from two different systems, were downsampled to a common sampling rate. Subsequently, cross-correlation analysis was performed to temporally synchronize the datasets.The filtered data were then segmented into individual poling cycles using a threshold method based on the signal from the force sensors attached to the ski pole. The start of the poling phase was defined as 0% of a cycle, which corresponds to the moment the ski pole touches the ground, and the end of the recovery phase was defined as 100% of the cycle, which corresponds to the next Impact of the pole on the ground.

The recorded acceleration data from the sensors attached along the back make it possible to calculate the angulation of the upper body and thus the range of movement of the upper body, in particular its forward and backward inclination (flexion and extension). This makes it easier to analyze the flexibility of the upper body in relation with different sitting positions. A sitting position with a pronounced forward tilt may indicate an increased range of motion and free movement of the upper body. However, it should be noted that a highly inclined sitting position may also be associated with increased muscle activation, which could be considered a disadvantage.

To investigate whether there is a significant difference in the range of motion during the three sitting positions, the Friedman test, a non-parametric statistical test, was chosen due to the limited dataset.

3 Results and Discussion

In figure 4 , the angulation of the entire upper body of a representative subject is presented. It is visible that the angulation during the three seated positions tends to be similar. However, there are differences in the duration and timing of the individual extension and flexion phases, as well as the range of motion.

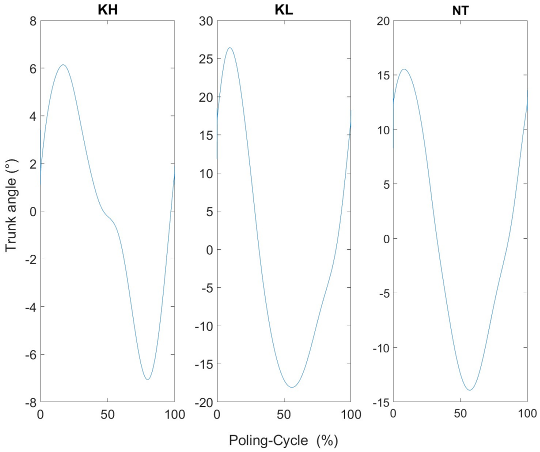

Fig. 4: Range of motion of the entire upper body of a representative subject during the three sitting positions.

When examining the movement during the KH position, the following can be observed: The upper body movement results in a flexion, when the body is leaning forward. This flexion begins just before the end of the poling cycle at around 90% of the cycle, and lasts until approximately 20% of the cycle, which corresponds to the end of the polling phase. After this, from about 20% to 50% of the cycle, the upper body is brought back to an upright position.Then the extension phase begins, during which the body is leaned backwards and lasts until about 90% of the cycle. The forward and backward inclination angles in the KH position are significantly lower than those in the KL and NT positions. The greatest range of motion is observed in the KL position. Additionally, it can be noted that the duration of the flexion phase in the KL and NT positions is shorter compared to that in the KH position.

In figure 5 , the same observations mentioned above can be seen. The greatest ROM is shows in the KL position among all test subjects, followed by the neutral position. The KH position demonstrates the limited ROM.

In the investigation of the hypothesis regarding whether there is a significant difference in the range of motion among the three sitting positions, the results of the Friedman test indicated a significant difference ($P < 0.05$). This finding also confirms the observed differences presented in the figure above.

The results establish that the upper body is optimally positioned in the KL position. The angulation and, consequently, the overall ROM were greatest among all test subjects during the KL position. This suggests that the subjects utilized their entire upper body optimally for force production during

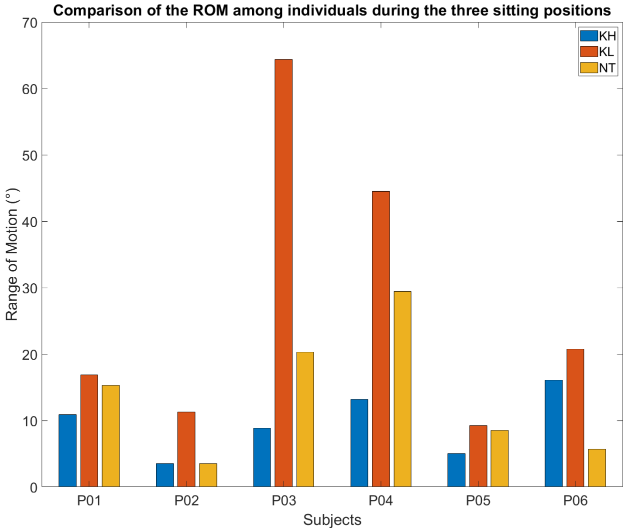

Fig. 5: Range of motion of the individual subjects during the three conditions.

the poling phase while in the KL position. The static analysis further substantiates this relationship by showing a significant difference.

Previous studies investigating the differences between the KH and KL positions in terms of force production also corroborate these findings. The differences in the values can be attributed to the elevated position of the upper body and the improved capacity to utilize the core musculature in the KL position. Initiating the pole from a higher position in the KL stance allows for effective weight transfer onto the poles, resulting in higher force output in a shorter time frame. In contrast, the KH position demands a more intense engagement of the triceps, thereby extending the duration of the poling phase and increasing the workload on these muscles [6,7,8].

4 Conclusion

This study examined the differences in the ROM of the upper body in Paralympic cross-country skiing across various sitting positions. The results consistently highlight that the KL position allows for a greater overall ROM compared to the KH position, indicating a more optimal biomechanical alignment for efficient movement during the poling phase. The study revealed that subjects in the KL position utilized a higher tilt angle, facilitating better force transfer onto the poles and resulting in enhanced movement efficiency. In contrast, the KH position demonstrated a more restricted range of motion, which could negatively affect performance. In summary, the findings indicate that the KL position maximizes upper body ROM and overall efficiency in poling. Future analyses of ROM in relation to muscle activation patterns and force production could provide deeper insights and added value to our understanding of performance in adaptive sports.

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Author Statement

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References

[1] Gastaldi, L., Pastorelli, S., Frassinelli, S. (2012). A biomechanical approach to paralympic cross-country sit-ski racing. Clinical journal of sport medicine : official journal of the Canadian Academy of Sport Medicine, 22(1), 58–64. https://doi.org/10.1097/JSM.0b013e31824202d3
[2] Paralympic Committee (IPC) and World Para Nordic Skiing (2017).
[3] Milano Cortina 2026 home. International Paralympic Committee. (n.d.). https://www.paralympic.org/milano-cortina-2026
[4] Pernot, H. F., Lannem, A. M., Geers, R. P., Ruijters, E. F., Bloemendal, M., Seelen, H. A. (2011). Validity of the test-table-test for Nordic skiing for classification of paralympic sit-ski sports participants. Spinal cord, 49(8), 935–941. https://doi.org/10.1038/sc.2011.30
[5] Lajunen, K., Rapp, W., Ahtiainen, J. P., Lindinger, S. J., Linnamo, V. (2020). Effect of Sitting Posture on Sit-Skiing Economy in Non-disabled Athletes. Frontiers in sports and active living, 2, 44. https://doi.org/10.3389/fspor.2020.00044
[6] Lajunen, K., Rapp, W., Ahtiainen, J. P., Lindinger, S. J., Linnamo, V. (2020). Effect of Sitting Posture on Sit-Skiing Economy in Non-disabled Athletes. Frontiers in sports and active living, 2, 44. https://doi.org/10.3389/fspor.2020.00044
[7] Lund Ohlsson, M., Laaksonen, M. S. (2017). Sitting position affects performance in cross-country sit-skiing. European journal of applied physiology, 117(6), 1095–1106. https://doi.org/10.1007/s00421-017-3596-y
[8] Hirsch, L., Barioudi, H., Wintergerst, D., Rombach, R., Rapp, W., Felderhoff, T., Mrachacz-Kersting, N. (2024). Pushing forward: exploring the impact of the sitting position on muscle activation patterns and force generation during paralympic sit-cross-country skiing. Frontiers in sports and active living, 6, 1441586. https://doi.org/10.3389/fspor.2024.1441586