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REGULAR PAPER

Kinematic Comparison of Double Poling Techniques Between National and College Level Cross-Country Skiers Using Wearable Inertial Measurement Unit Sensors

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Abstract

This study aimed to analyze and compare the hip, knee, and elbow joint movements during the double poling (DP) technique in cross-country skiing using a wearable inertial measurement unit (IMU) sensor on a real snow skiing track. Six national players (NP) and five college players (CP) participated in this study. The joints angles were calculated using the data from IMU sensors on a 145 m skiing course with 10° slope using the DP technique. In addition, the parameters of the DP phase were estimated. Then, all parameters were compared between the NP and CP groups. The hip and knee joint angles in the NP groups were significantly larger than the CP groups. However, there was no intergroup difference in elbow joint range of motion (ROM). Moreover, the cycle length and cycle velocity was higher in the NP group than the CP group. The results showed that the NP group had higher speed and longer cycle length with greater flexion angles in the hip and knee joints. The wearable IMU sensor was used to analyze the motions during DP skiing on the snow skiing slope, which can provide more realistic detailed analysis of the skiing movements. This study provides the comparison analysis of the main parameters between the two different skilled skiers groups, which may help coaches and players improve skiing performance.

Keywords IMU sensor · Double poling · Joint angle · Kinematic analysis · Skiing

1 Introduction

Cross-country (XC) skiing is the one of the most popular endurance sports in the world [1, 2], which requires high-speed techniques and flexible tactical movements with a high aerobic capacity to achieve successful performance [3–5]. The appropriate sub-techniques are also important and used to manage various terrain and snow conditions [6, 7]. In addition, as the proportion of sprint and mass start games has increased since the 2000s, a high level of skill is needed to increase velocity later in the game [8].

XC skiing events are divided into classic and freestyle, where the sub-techniques used in the classic event include double-poling (DP), diagonal stride (DS), and kick double-poling (KDP) [9–11]. The sub-techniques of the freestyle event include V1 technique (poling on every second leg stroke), V2 technique (poling on every leg stroke), no pole skate (only the legs are used) [9, 10]. The poling is the main technique used in both classic and freestyle events [12, 13]. In particular, the importance of the DP technique is emphasized in classical events as the speed of modern skiing can reduce the physiological burden and result in high speed; thus, the amount of DP technique used during the competition is increasing [14, 15]. Biomechanically, pole angle, joint height from the ground, and the range of motion (ROM), as well as angular velocities of the lower extremities are important in the DP technique [16, 17]. To achieve high speed, the upper and lower bodies should have a proper flexion, and the

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upper body must transmit maximum force to the pole to gain momentum [5, 10, 16, 18].

Most of the existing biomechanical studies on DP have simulated XC skiing using roller skis on treadmills in specific laboratories [1, 19–21]. These laboratory-based studies were able to accurately assess physiological and biomechanical parameters according to specific experimental procedures, but they were unable to facilitate a detailed analysis of the movement of XC skiers in real snow conditions. In-field motion analysis studies have generally utilized a video camera [10,22,23]. However, this method requires significant time and cost.

Kinematic analysis is an important method for determining skiing performance. The main determinant of performance between fast and slow skiers is not strength and power, but the timing and application of poling during skiing. The form of faster skiers demonstrates better shoulder-elbow-pole position and vertical pole angles when performing double poling, resulting in longer poling cycles, poling length, and poling recovery time [14, 17, 24]. The kinematic parameters of the main joint may differ between different skill level skiers. However, there are few studies that have investigated the kinematic characteristics between different skill level XC skiers.

Recent developments in sensor application allow monitoring of human movements in various environments and are utilized in other winter sports [25–28]. For XC skiing, there are a few studies that have used the inertial measurement unit (IMU) sensor for measuring the only pole or trunk motion with the one or two sensors [28–30]. To our knowledge, no previous studies have investigated the three-dimensional (3D) kinematics during XC skiing on real snow slopes. In this study, we investigated the joints angles of hip, knee, and elbow during the XC skiing course for national and college level skiers using multiple IMU sensors.

2 Materials and Methods

2.1 Validation of the Wearable IMU Sensors

In order to estimate the accuracy of the IMU sensors, the joint angle values compared between the wearable IMU sensor system and conventional optical camera system. Ten male subjects (age, 26 ± 3.7; height, 172.2 ± 4.1; weight, 71.2 ± 9.8) participated. The wearable IMU sensor system consisted of 13 IMU sensors. The conventional optical motion capture system consisted with ten cameras. Thirteen IMU sensors and 37 reflective markers were attached to the subjects body according to the previous study [31]. Walking motion data were captured during the full gait cycle from a right hell strike to the next right heel strike with subject-preferred speed [31]. The averaged magnitudes of the flexion angles of hip, knee, and elbow joint of ten subjects were compared between the wearable and conventional systems in terms of Pearson's correlation coefficient (r) and the root mean squared error (RMSE) using the Matlab software.

2.2 Participant Information for Skiing Experiment

Six national players (NP) and five college players (CP) participated in this study, all of whom had no musculoskeletal injuries within the past year. All participants were male and critical information is summarized in Table 1. All participants were recruited with informed consent from the Korean Ski Association (KSA).

2.3 Experiment Procedure

In this study, three-axis acceleration data and three-axis gyroscope data during XC skiing using the classical DP technique were collected using a wearable motion capture system (Wearnotch, Notch Interface Inc), which consisted of 13 IMU sensors. The sensors were attached the body segments using straps, as shown in Fig. 1.

The XC skiing experiment was conducted on the 145-m uphill snow ski-track at XC Ski course (Sprint and Distance Course), Pyeongchang Winter Olympic Games under the supervision of an experienced coach. The uphill inclination was approximately 10°. The participants were wearing the IMU sensors, their own costumes, skis, and pole. Pole length was set to 85% of the magnetic height according to the Fédération Internationale de Ski (FIS) regulations. Skiers were asked to perform the speed test and glide wax and kick wax test to minimize the speed differences. Before starting each season, skiers were asked to stand straight in a steady pose until the calibration process was successfully finished under supervision by a coach. During the calibration process, the system automatically checked that the sensor's orientation became consistent with the predefined reference coordinate system.

2.4 Data Analysis

For each participant, whole-body motion data were recorded at a sampling rate of 100 Hz. The sensor raw data were then transferred to an Android tablet by Bluetooth connection after each skiing attempt, then sent to a server computer for processing using Matlab® R2015a (The Mathworks Inc., USA). The noise of acceleration

Table 1 Physical characteristics of participants

Group	Height (m)	Weight (kg)	Body fat (%)	Career (years)
NP	175.6	70.1	11.5	13.5
CP	175.8	66.8	12.5	9.4

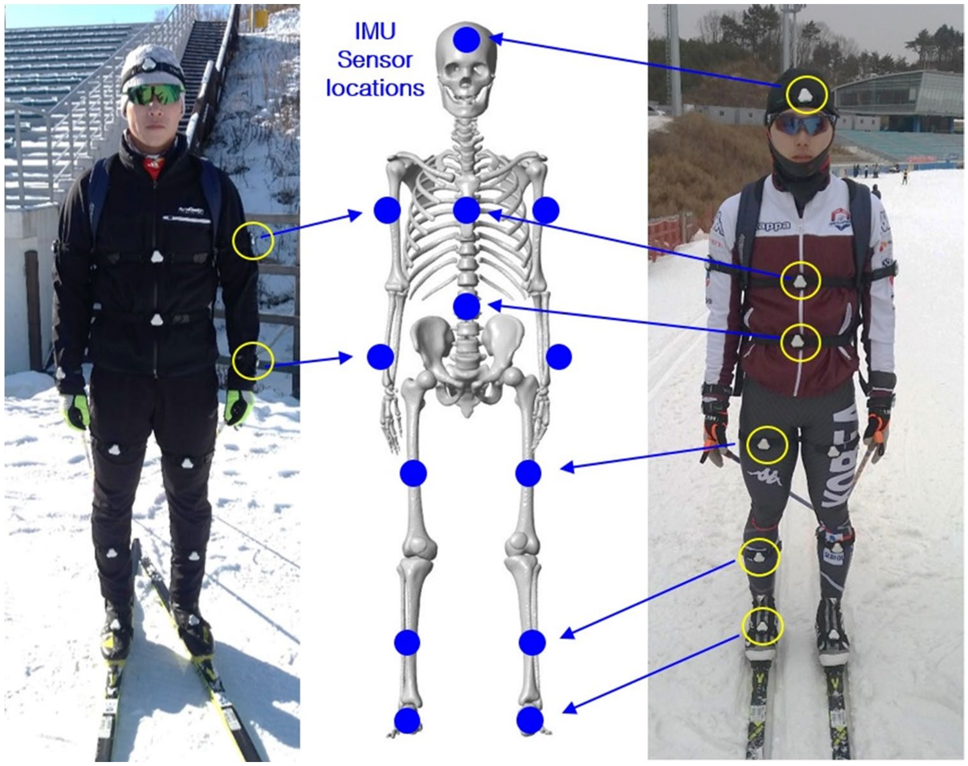

Fig. 1 IMU sensor locations on the participant

data was removed by using a 4th-order low-pass Butterworth filter with a cut-off frequency of 5 Hz. In order to estimate the joint angle using sensor raw data, an in-house joint angle calculation algorithm with Madgwick filter was developed based on a previous study [32]. The joint angles were calculated as Euler angles of the distal segment reference frame relative to the proximal segment reference frame [26]. The motions of the hip, knee, and elbow joints in the sagittal plane were expressed as follows: hip flexion (+)/extension (−), knee flexion (+)/extension (−), and elbow flexion (+)/extension (−) (Fig. 2).

After calculating the joint angles, the DP phases were defined through the skiing course based on the previous studies [10, 16]. The one DP cycle was defined as the period from the start of the pole ground contact to the start of subsequent pole ground contact [10, 16] (Fig. 3). Each DP cycle includes the poling thrust and recovery phases. Each cycle were normalized and divided into 100 steps. For each individual, joint angle data for all DP cycles were averaged. The averaged data of each participant were averaged again for NP and CP groups, respectively. Furthermore, we compared the range of the joint angles, cycle time, poling and recovery times, cycle length, cycle velocity for NP and CP groups. The poling and recovery times were defined when elbow reached maximum extension. The cycle velocity was calculated by distance traveled per cycle, where the travelled distance was estimated by using the hip joint movements.

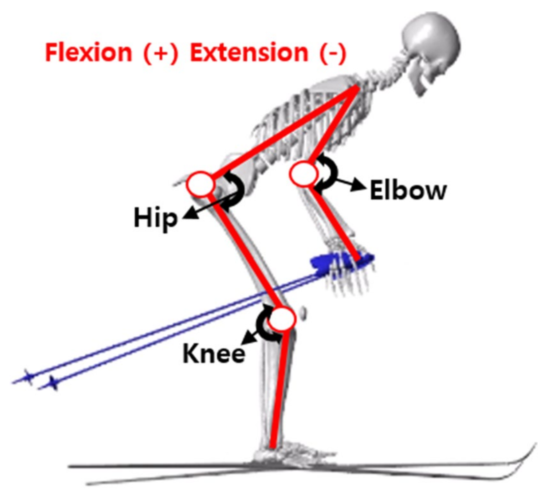

Fig. 2 Hip, knee, and elbow flexion angle definition

2.5 Statistical analysis

The experimental results were tested for significant intergroup differences in degree of flexion through independent sample t-tests using the Statistical Package for Social Science (SPSS Inc., Chicago IL, USA). Significant probability was set at $p < 0.05$.

3 Results

3.1 Validation of the Wearable IMU Sensors

The right and left hip, knee, elbow flexion angles were strongly correlated between wearable IMU sensors and the conventional optical system with RMSE ≤ 5.8% and correlation of r ≤ 0.99 (Fig. 4).

3.2 Flexion angle of the Hip, Knee, and Elbow Joints

The hip, knee, and elbow joint angles are shown in Figs. 5, 6 and 7. The ROM of the right/left hip, knee, and elbow were 102.7°/106.9°, 47.4°/38.9° and 71.9°/75.8°, respectively, in the NP groups, and 85.6°/89.0°, 42.8°/32.3° and 73.9°/66.6°, respectively, in the CP groups (Figs. 5, 6 and 7 and Table 2). For the NP skiers, hip and knee joints were more flexed for 17.1°-17.9° and 4.6°-6.6° compared to the CP skiers ($p < 0.01$), possibly indicating a higher activation

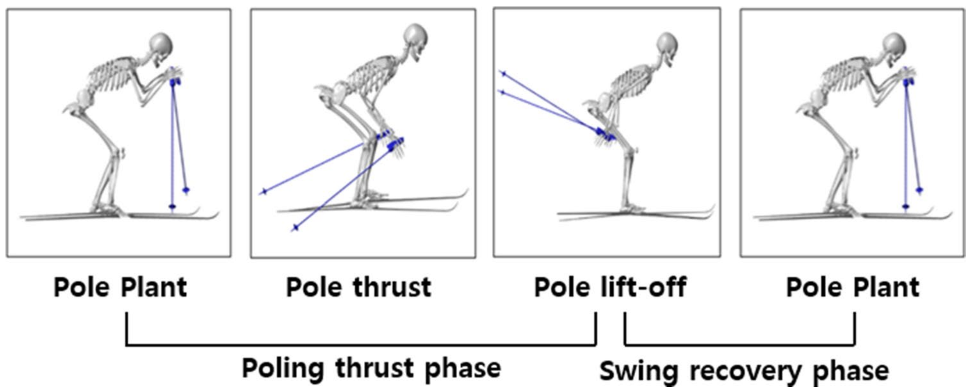

Fig. 3 Double Poling definition

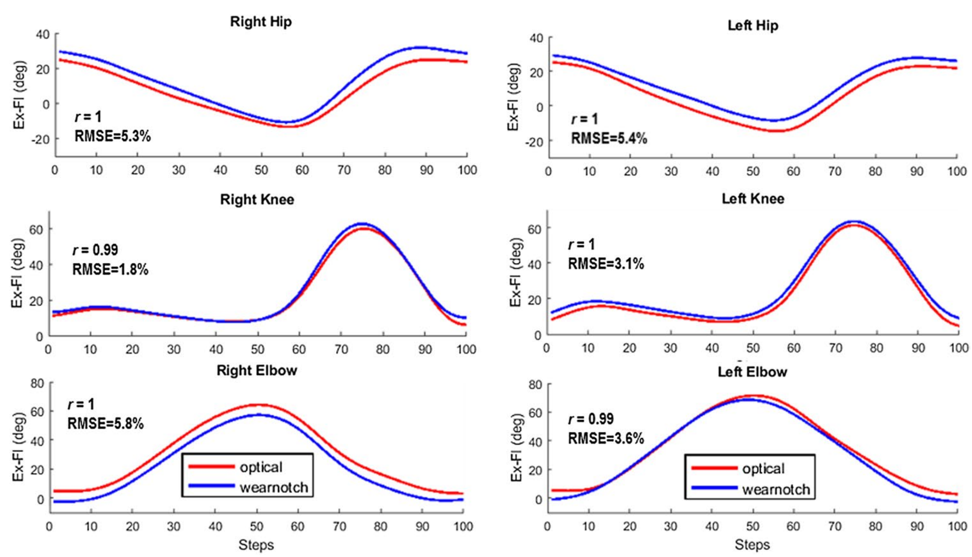

Fig. 4 Right and left hip flexion angle for national (NP) and college level players (CP)

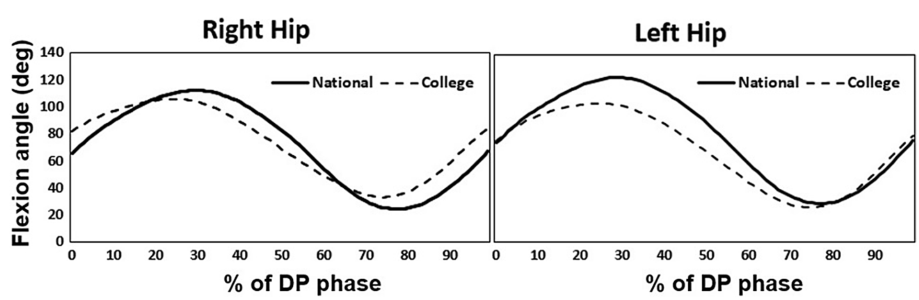

Fig. 5 Right and left hip flexion angle for national (NP) and college level players (CP)

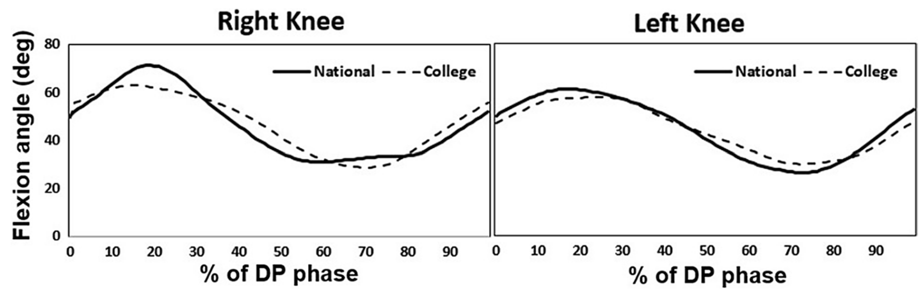

Fig. 6 Right and left knee flexion angle for national (NP) and college level players (CP)

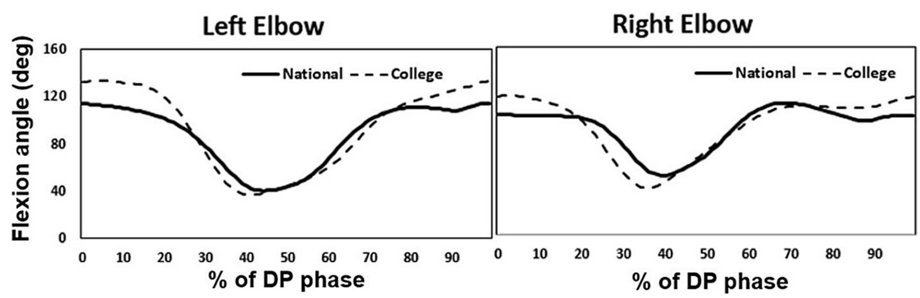

Fig. 7 Right and left elbow flexion angle for national (NP) and college level players (CP)

Table 2 The ROM of hip, knee, and elbow joints

Joints	NP	CP	p-value
Right hip	102.7 ± 19.2	85.6 ± 12.1	0.01**
Left hip	106.9 ± 18.1	89.0 ± 8.0	0.01**
Right knee	47.4 ± 11.3	42.8 ± 6.6	0.03*
Left knee	38.9 ± 12.4	32.3 ± 8.8	0.01**
Right elbow	71.9 ± 17.1	73.9 ± 24.2	0.79
Left elbow	75.8 ± 12.2	66.6 ± 13.5	0.09

*p < 0.05 vs. pre, **p < 0.01 vs pre

Table 3 The parameters of national players and college players

Joints	NP	CP	p-value
Cycle time (s)	0.84 ± 0.11	0.73 ± 0.11	0.00***
Poling Time (s)	0.36 ± 0.05	0.31 ± 0.04	0.00***
Recovery time (s)	0.48 ± 0.06	0.42 ± 0.06	0.08
Cycle length (m)	4.32	3.56	0.05*
Cycle velocity (m/s)	5.08	4.81	0.33

*p < 0.05 vs. pre, **p < 0.01 vs. pre, ***p < 0.01 vs. pre

of the core muscles and rapid force production during the poling. However, there was no significant intergroup difference in the flexion of the elbow joints ($p > 0.05$), the NP skiers had a higher elbow flexion of 2.0°-9.2°. In Table 2, ROM of the hip, knee, and elbow joints for NP and CP are summarized with a significant level of 0.05.

3.3 Parameters of the DP Phase

Table 3 summarizes the parameters of the DP phase for NP and CP groups with p-value. The cycle times were 0.84 ± 0.11 s and 0.73 ± 0.11 s for the NP and CP group, respectively ($p < 0.01$). The poling and recovery times for NP and CP were 0.36 ± 0.05 s and 0.48 ± 0.06 s ($p < 0.01$), and 0.31 ± 0.04 s and 0.42 ± 0.06 s, respectively ($p > 0.05$). The estimated cycle lengths were 4.32 m and 3.56 m for NP and CP groups, respectively ($p < 0.05$). The average cycle velocity was 5.08 m/s in the NP group and 4.81 m/s in the CP group ($p > 0.05$). In general, the NP group was rated technically better and exhibited 15% longer cycle time, 16% longer poling time, 21% longer cycle length, and 5% higher cycle rate compared to CP group, which allows to produce more power while skiing faster and longer.

4 Discussion

The current study showed that skilled skiers exhibited a higher ROM of the hip and knee joints, longer cycle time, longer cycle length and faster cycle rate. The higher ROM of the lower extremities with a longer cycle characteristics allows to produce power efficiently during the skiing than the college athletes. These results were similar to that previous studies where they reported that ROMs of the main joints are known to be closely related to the DP speed and length [16, 17, 21]. Holmber et al. [2005] reported that increased ROM in the hip and elbow increased the force transmitted to the poles during poling preparation phase, which led to increase the poling speed and length. However, if the elbow and knee joint ROM is limited or fluidity is reduced, cycling frequency of the DP increased and the poling speed, length, phase, and recovery time decreased [16, 17]. Therefore, it can be determined that the ROM difference between the hip and knee joints affected DP speed and length. In addition, when the NP group had a lower poling frequency and higher poling recovery time than the CP group, the difference in knee and hip joint ROM affects poling frequency and recovery time along with poling speed and length.

On the other hand, in DP, the recovery time is larger than the polling time, which is known to reduce muscle fatigue. One-cycle DP time required about 0.1 s longer in the NP group than in the CP group, but the distance was increased by the increased degree of flexion. In this study, however, the intergroup difference between the poling time and recovery time did not appear to be due to the slope of the experimental course. As the slope increases, the unchanged poling phase and recovery phase durations tended to be shorter, thereby increasing the speed by decreasing the polling time and recovery time [18].

Most of existing biomechanical studies of the XC skiing have been conducted in indoor laboratories using treadmills, roller skis, skierometers, and electromyography [1, 14, 19–21]. These studies were limited compared to the detailed joint movement analysis obtained while skiing on the snow skiing track. In this study, we demonstrated the use of IMU sensors for movement analysis during skiing in a real snow condition, and confirmed that hip and knee joint ROM influences DP speed, length, and frequency as in previous studies. We obtained main joint motion data during skiing on a real snow field. It should be noted that flexion of the left hip and right knee joints were higher than the right hip and left knee joints. The reason for the difference can be explained by the phenomenon of maintaining the body center through the horizontal slope combined with the vertical slope in the course.

5 Conclusion

We investigated the hip, knee, and elbow joint motions, as well as parameters of the DP technique in XC skiing, and compared those parameters between two different skiing skill groups. The wearable IMU sensor was used to analyze the motions during DP skiing on a snow skiing slope, which can provide more realistic detailed analysis of the skiing movements. The results showed that the NP group has a higher speed and longer cycle length with greater flexion angles of the hip and knee joints. Therefore, it is important to focus on increasing the joint ROM and angular velocity while coaching young athletes. However, there was not significant difference observed between the two groups on the elbow flexion. This study provides the comparison analysis of the main parameters between the two different skilled skier groups, which may help coaches and players to improve skiing performance. Finally, the wearable sensor-based measurement method could be applied to many other sports and it will be helpful for young athletes to improve their technique and performance.

Declaration

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Pellegrini, B., Zoppirolli, C., Bortolan, L., Holmberg, H. C., Zamparo, P., & Schena, F. (2013). Biomechanical and energetic determinants of technique selection in classical cross-country skiing. *Human Movement Science, 32*(1), 1415–1429.
2. Danielsen, J., Sandbakk, Ø., McGhie, D., & Ettema, G. (2018). The effect of exercise intensity on joint power and dynamics in ergometer double-poling performed by cross-country skiers. *Human Movement Science, 57,* 83–93.
3. Millet, G. P., Boissiere, D., & Candau, R. (2003). Energy cost of different skating techniques in cross-country skiing. *Journal of Sports Science, 21*(1), 3–11.
4. Sandbakk, Ø., & Holmberg, H. C. (2014). A reappraisal of success factors for Olympic cross-country skiing. *International Journal of Sports Physiology, 9*(1), 117–121.
5. Holmberg, H. C. (2015). The elite cross-country skier provides unique insights into human exercise physiology. *Scandavian Journal of Medicine & Science in Sports, 25,* 100–109.
6. Solli, G. S., Tønnessen, E., & Sandbakk, Ø. (2017). The training characteristics of the world's most successful female cross-country skier. *Frontiers in Physiology, 8,* 1069.
7. Sandbakk, Ø., & Holmberg, H. C. (2017). Physiological capacity and training routines of elite cross-country skiers: Approaching the upper limits of human endurance. *International Journal of Sports Physiology, 12*(8), 1003–1011.
8. Sandbakk, Ø., Holmberg, H. C., Leirdal, S., & Ettema, G. (2011). The physiology of world-class sprint skiers. *Scandavian Journal of Medicine & Science in Sports, 21,* e9–e16.
9. Bilodeau, B., Rundell, K. W., Roy, B., & Boulay, M. R. (1996). Kinematics of cross-country ski racing. *Medicine & Science in Sports & Exercise, 28*(1), 128–138.
10. Nilsson, J., Tveit, P., & Eikrehagen, O. (2004). Cross-Country Skiing: Effects of speed on temporal patterns in classical style and freestyle cross-country skiing. *Sports Biomechanics, 3*(1), 85–108.
11. Stöggl, T., Kampel, W., Mueller, E., & Lindinger, S. (2010). Double-push skating versus V2 and V1 skating on uphill terrain in cross-country skiing. *Medicine & Science in Sports & Exercise, 42*(1), 187–196.
12. Rusko, H. (2008). *Handbook of sports medicine and science, cross country skiing*. John Wiley & Sons.
13. Alsobrook, N. G., & Heil, D. P. (2009). Upper body power as a determinant of classical cross-country ski performance. *European Journal of Applied Physiology, 105*(4), 633–641.
14. Stöggl, T., Mueller, E., Ainegren, M., & Holmberg, H. C. (2011). General strength and kinetics: Fundamental to sprinting faster in cross country skiing? *Scandavian Journal of Medicine & Science in Sports, 21*(6), 791–803.

15. Stöggl, T., Pellegrini, B., & Holmberg, H. C. (2018). Pacing and predictors of performance during cross-country skiing races: A systematic review. *Journal of Sport and Health Science, 7*(4), 381–393.
16. Holmberg, H. C., Lindinger, S., Stöggl, T., Eitzlmair, E., & Müller, E. (2005). Biomechanical analysis of double poling in elite cross-country skiers. *Medicine & Science in Sports & Exercise, 37*(5), 807–818.
17. Smith, G. A., Fewster, J. B., & Braudt, S. M. (1996). Double poling kinematics and performance in cross-country skiing. *Journal of Applied Biomechanics, 12*(1), 88–103.
18. Millet, G. Y., Hoffman, M. D., Candau, R. B., & Clifford, P. S. (1998). Poling forces during roller skiing: Effects of grade. *Medicine & Science in Sports & Exercise, 30*(11), 1637–1644.
19. Stöggl, T., Lindinger, S., & Müller, E. (2007). Analysis of a simulated sprint competition in classical cross country skiing. *Scandavian Journal of Medicine & Science in Sports, 17*(4), 362–372.
20. Fabre, N., Balestreri, F., Leonardi, A., & Schena, F. (2010). Racing performance and incremental double poling test on treadmill in elite female cross-country skiers. *Journal of Strength & Conditioning Research, 24*(2), 401–407.
21. Holmberg, H., Lindinger, S., Stoggl, T., Bjorklund, G., & Muller, E. (2006). Contribution of the legs to double-poling performance in elite cross-country skiers. *Medicine & Science in Sports & Exercise, 38*(10), 1853.
22. Zory, R., Vuillerme, N., Pellegrini, B., Schena, F., & Rouard, A. (2009). Effect of fatigue on double pole kinematics in sprint cross-country skiing. *Human Movement Science, 28*(1), 85–98.
23. Zoppirolli, C., Bortolan, L., Stella, F., Boccia, G., Holmberg, H. C., Schena, F., et al. (2018). Following a long-distance classical race the whole-body kinematics of double poling by Elite Cross-Country Skiers are altered. *Frontiers in Physiology, 9,* 978.
24. Stöggl, T., & Holmberg, H. C. (2011). Force interaction and 3D pole movement in double poling. *Scandavian Journal of Medicine & Science in Sports, 21*(6), e393–e404.
25. Purevsuren, T., Khuyagbaatar, B., Kim, K., & Kim, Y. H. (2018). Investigation of knee joint forces and moments during short-track speed skating using wearable motion analysis system. *International Journal of Precision Engineering and Manufacturing, 19*(7), 1055–1060.
26. Khuyagbaatar, B., Purevsuren, T., Park, W. M., Kim, K., & Kim, Y. H. (2017). Interjoint coordination of the lower extremities in short-track speed skating. *Proceedings of the Institution of Mechanical Engineers, Part H, 231*(10), 987–993.
27. Krüger, A., & Edelmann-Nusser, J. (2009). Biomechanical analysis in freestyle snowboarding: application of a full-body inertial measurement system and a bilateral insole measurement system. *Sports Techology, 2*(1–2), 17–23.
28. Fasel, B., Favre, J., Chardonnens, J., Gremion, G., & Aminian, K. (2015). An inertial sensor-based system for spatio-temporal analysis in classic cross-country skiing diagonal technique. *Journal of Biomechanics, 48*(12), 3199–3205.
29. Marsland, F., Lyons, K., Anson, J., Waddington, G., Macintosh, C., & Chapman, D. (2012). Identification of cross-country skiing movement patterns using micro-sensors. *Sensors, 12*(4), 5047–5066.
30. Sakurai, Y., Fujita, Z., & Ishige, Y. (2016). Automatic identification of subtechniques in skating-style roller skiing using inertial sensors. *Sensors, 16*(4), 473.
31. Khurelbaatar, T., Kim, K., Lee, S., & Kim, Y. H. (2015). Consistent accuracy in whole-body joint kinetics during gait using wearable inertial motion sensors and in-shoe pressure sensors. *Gait & Posture, 42*(1), 65–69.
32. Madgwick, S. (2010). An efficient orientation filter for inertial and inertial/magnetic sensor arrays. *Report x-io and University of Bristol (UK), 25,* 113–118.

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