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Article

Cross-Country Ski Skating Style Sub-Techniques Detection and Skiing Characteristic Analysis on Snow Using High Precision GNSS

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Abstract: The comprehensive analysis of cross-country skiing races is a pivotal step in establishing effective training objectives and tactical strategies. This study aimed to establish a method for the classification of sub-techniques and analyzing skiing characteristics during cross-country skiing skating style timed races on snow using high-precision kinematic GNSS devices. The study involved attaching GNSS devices to the heads of two athletes during skating style timed races on cross-country ski courses. These devices provided precise positional data and recorded vertical and horizontal head movements and ground over velocity (VOG). Sub-techniques were classified by defining waveform patterns for G2, G3, G4, and G6 based on these data. The validity of classification was verified by comparing GNSS data with video analysis, a process that yielded classification accuracies ranging from 94.0% to 99.3% for G2, G3, G4, and G6. Notably, G4 emerged as the fastest technique, with sub-technique selection varying among skiers and being influenced by skiing velocity and course inclination. The study's findings have practical implications for athletes and coaches, as they demonstrate that high-precision kinematic GNSS devices can accurately classify sub-techniques and detect skiing characteristics during skate-style cross-country skiing races, thereby providing valuable insights for training and strategy development.

Keywords: high precision GNSS; cross-country skiing; skating techniques; sub-technique classification

1. Introduction

Cross-country skiing courses are designed to utilize natural terrain, including uphill, downhill, and flat sections, to reflect the athletes' technical, tactical, and physical abilities. [1]. Cross-country skiing has two main competition styles: classical style and skating style. Different gears, known as sub-techniques with distinct movements, are used in each competition style based on the course

inclination. The three significant sub-techniques in the skating style are G2, G3, and G4; G2 is employed on uphill sections and involves one asymmetrical poling action for every two leg actions; G3 is used on flat to gradual uphill sections and involves one poling action and one leg action; G4 is used flat sections and involves one symmetrical poling action for every two leg actions. [2,3]. Since each sub-technique provides different skiing velocities [3], strategic performance must select the sub-technique that maximizes skiing velocity depending on course inclination, muscle strength of the upper body, and gliding performance. It has been reported that upper body power and maximal oxygen uptake are necessary for sub-technique selection; both tend to show superior cross-country skiing performance in athletes with higher abilities[4–6].

However, what sub-techniques skiers use more frequently throughout a race has yet to be well known. It is practically challenging to video-capture skiers throughout the entire race. Determining the frequency of sub-technique use is an essential resource for determining the relationship between physical fitness, such as upper body power and maximal oxygen uptake, and the technical characteristics of individual athletes, which is also essential for developing training goals and tactics.

In a previous study of race analysis in skating style, Anderson et al. [3] utilized the Global Navigation Satellite System (GNSS) and video cameras to analyze sub-techniques, skiing velocity, cycle time (CT), cycle length (CL), and other relevant parameters during timed races. However, while accurate position data was available from GNSS data, the sub-technique analysis relied on video cameras, making capturing multiple skiers simultaneously throughout the course challenging. Furthermore, the weight of the measurement equipment, 1.64 kg, was a notable problem. Sakurai et al. [7] conducted a sub-technique classification of roller skis using inertial sensors. However, skiing velocity has yet to be clarified in this study. The Naos sensor developed by Archinisis integrates an inertial sensor, GNSS device, and barometric pressure sensor in a single compact device, enabling simultaneous data collection of ski technique, skiing velocity, and position information. Analysis has also been conducted using this device[8,9]. However, it has been reported that the GNSS positioning needs to maintain sufficient accuracy, which may cause errors in position information[10], and the accuracy of the measurements is not sure. These challenges highlight the need for a more effective and accurate method, which we aim to address in this study.

On the other hand, Takeda et al. [11] used a high-precision kinematic GNSS device to measure GNSS position information with extremely high precision to evaluate sub-technique classification and skiing velocity during a classical-style timed trial for the world's top-level male skier. In this study, the GNSS device was attached to the head, and technique classification was attempted based on the hypothesis that the vertical movement of the head is different for each sub-technique. They reported that they could classify the sub-techniques (double poling, diagonal stride, kick double poling, and herringbone) with 98% accuracy. Øyvind Gløersen et al. [12] used the same high-precision kinematic GNSS device and classified sub-techniques in skating style techniques based on vertical and horizontal head movement features. They reported correctly classifying sub-techniques G2, G3, and G4 with an accuracy of 92.1% to 97.1%. However, the study by Øyvind Gløersen et al. [12] attempted classification during roller skiing on paved trails. To the author's knowledge, no research has been done on the sub-technique classification of actual skating style on unstable snow surfaces. Since the head movement in the skating style does not differ much from one sub-technique to another compared to the classical style, it is crucial to capture head movements in detail and with high accuracy.

Position information measurement technology of GNSS devices has been improving at an accelerated pace in recent years. Accordingly, momentum and running speed analyses have been conducted using GNSS devices in many sports, such as soccer and rugby. Most of these GNSS devices use relative positioning GPS (differential GPS), which has a significant measurement error of about 1 m, and the measurement frequency is generally 10 Hz [13]. Sports activities are high speed, and to detect slight differences in skiing velocity and position information, it is necessary to measure position information with high accuracy and to have a high measurement frequency. This point was also pointed out by Takeda et al. [11] in another study of the cross-country skiing sub-technique. Miyamoto et al. developed a compact, lightweight, low power consumption, and 10 Hz update rate post-processing kinematic (PPK) GNSS logger (AT-H-02, AOBA Technologia LLC, Japan) that is suitable for skiing measurements [14]. The AT-

H-02 does not perform positioning calculations for navigation commonly performed by GNSS devices, but it specializes in logging the raw data required for PPK [14]. Kinematic positioning based on carrier phase measurements provides higher accuracy than differential GPS, reaching sub-centimeters. Furthermore, a GNSS logger (simpleRTK3B Pro, ArduSimple, Spain) has been developed, which maintains its size, weight, and measurement accuracy while significantly increasing the sampling frequency from the traditional 10 Hz to 100 Hz. This advancement of GNSS technologies enhances temporal resolution and unprecedented precision in data acquisition, enabling more accurate classification of sub-techniques in skating style performed on unstable snow surfaces. We hypothesized that this high-precision GNSS device could accurately classify sub-techniques in cross-country ski skating style. Based on this, the present study used a high-precision kinematic GNSS device to classify sub-techniques and analysis of skiing characteristics in cross-country ski skating style.

2. Materials and Methods

2.1. Overall Design

Two male athletes (Subject A and Subject B) participated in a skating style timed race on the Ikenotaira cross-country ski course in Japan, which is 4.1 km long (five laps with the first lap being 0.9 km and the second to fifth laps being 0.8 km each, Figure 1). Subject A is a former member of the Japanese national team, and Subject B is an elite athlete in the Japanese U-15 category. The subjects used their own skis, poles, and boots. A GNSS device was attached to the subjects to obtain head position data during the timed race. The GNSS device consisted of an antenna (Lightweight helical GNSS Triple band + L-band antenna, ArduSimple, Spain, Size: 40 mm φ $\times$ H82.8 mm, Weight: 25 g) and a receiver (simpleRTK3B Pro, ArduSimple, Spain, Size: W59 mm $\times$ D87 mm $\times$ H33 mm, Weight: 137 g). The antenna was attached to the subjects' heads, and the receiver was stored in a small bag at their waist (Figure 2). The receiver is equipped with a GNSS module Mosaic-X5 (Septentrio, Belgium), capable of performing RTK positioning at a maximum sampling frequency of 100 Hz. The positioning accuracy is 0.6 cm + 0.5 ppm horizontally and 1 cm + 1 ppm vertically. To enable the receiver to communicate with the base station (NTRIP Caster/NTRIP Server) and obtain correction information (RTCM), a mobile router (Aterm MP01LN, NEC, Japan, Size: W50 $\times$ H12 $\times$ D91 mm, Weight: 71 g) was stored in the small bag along with the receiver. During the timed race, the subjects were followed by a snowmobile from behind, and all sub-techniques were recorded throughout the entire race using a video camera (Hero9, GoPro, America). This study was conducted with the approval of the Ethics Committee of Doshisha University (No. 23042).

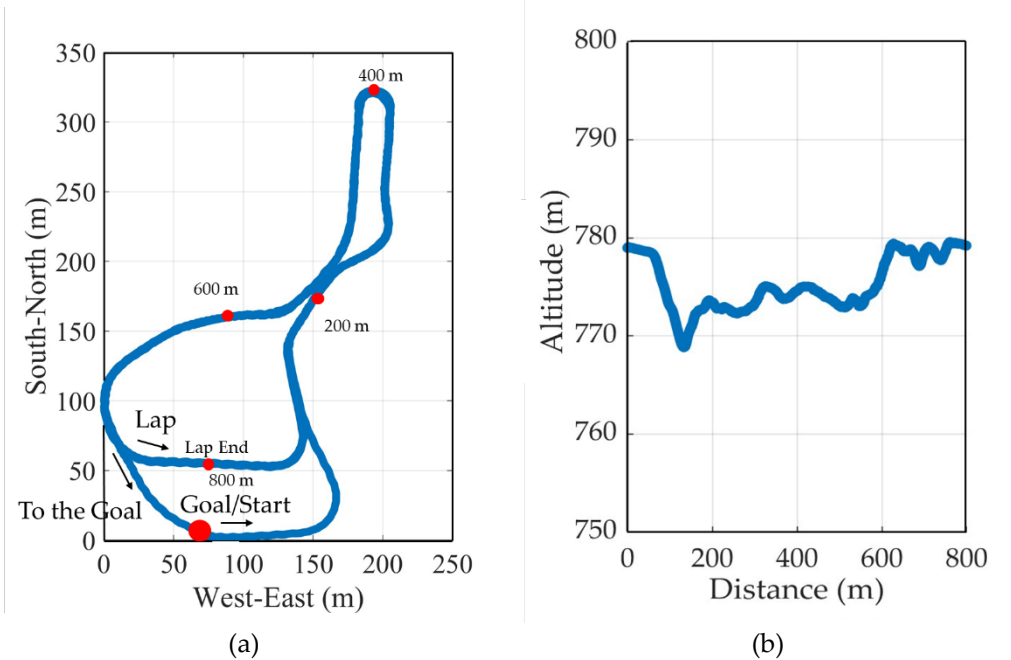


Figure 1. These figures show the Ikenotaira cross-country ski course, Japan used in this study. The plotted data was obtained from the study subject, covering one lap of 0.8 km. These figures show the course profile's plan view data(a) and course inclination data(b).

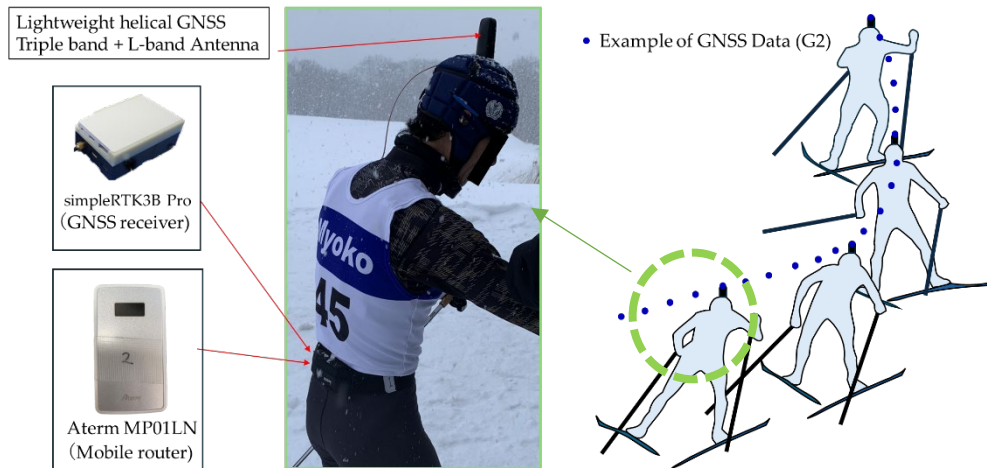


Figure 2. This picture and image show the experimental setup. The GNSS antenna was attached to the skier's head, and the receiver and mobile router were stored in a small bag at the skier's waist. This setup obtained head positioning data (latitude, longitude, altitude, and VOG) during the timed race.

2.2. Data Processing

NMEA messages obtained the trajectory of head movement relative to latitude, longitude, altitude, and VOG during the timed race, and the data analysis was conducted using MATLAB 2024a.

The movement of the head obtained from GNSS data includes the influence of course inclination and curves; therefore, removing these effects allows for the trajectory of pure head movement. The course inclination was derived by calculating a moving average from the altitude data. We used a sliding window approach with a window size of $2k + 1$ data points centered around each data point (where i represents a specific data point). In this study, k was set to 55 (1.1 seconds). Course inclination is given by:

$$\text{Course Inclination}(i) = \frac{1}{2k + 1} \sum_{j=i-k}^{i+k} \text{alt}(j) \quad (1)$$

With this procedure, it was possible to draw the course inclination for the entire course, as shown in Figure 1b. The change in the trajectory of the net vertical movement of the head was extracted by subtracting the course inclination data from the altitude data obtained from GNSS[11].

$$\begin{aligned} \theta_{\text{GNSS}}(i) &= \text{atan2}(v_i(2), v_i(1)) \\ \rho(i) &= \sqrt{v_i(1)^2 + v_i(2)^2} \end{aligned} \quad (2)$$

$$\theta_{\text{ave}}(i) = \frac{1}{2m + 1} \sum_{j=i-m}^{i+m} \theta_{\text{GNSS}}(j) \quad (3)$$

$$\theta_{\text{net}}(i) = \theta_{\text{GNSS}}(i) - \theta_{\text{ave}}(i) \quad (4)$$

$$\text{Net horizontal movement}(i + 1) = \text{Net horizontal movement}(i) + \rho(i) \cdot \sin(\theta_{\text{net}}(i)) \quad (5)$$

When attempting to remove the effects of course curves using a similar method with latitude and longitude data, the influence of the subject's horizontal movements was reflected, making it

challenging to smoothly represent the changes in course curves. Therefore, the calculation was performed using the following procedure: First, the LLH (latitude, longitude, altitude) coordinates are converted into the ENU (East-North-Up) coordinates ($v_i(1)$, $v_i(2)$, $v_i(3)$) using the given latitude, longitude, and altitude with the MATLAB function `llh2enu`. Here, $v_i(1)$ represents the eastward component, $v_i(2)$ represents the northward component, and $v_i(3)$ represents the upward component. Next, the horizontal components of the ENU coordinates ($v_i(1)$, $v_i(2)$) are converted into polar coordinates ($\theta_{\text{GNSS}}(i)$, $\rho(i)$) by Equation (2). Like Equation (1), The moving average of θ_{GNSS} is then computed to derive θ_{ave} by Equation (3). In this study, m was set to 52 (1.04 seconds). By subtracting $\theta_{\text{ave}}(i)$ from $\theta_{\text{GNSS}}(i)$, the net angle change $\theta_{\text{net}}(i)$ is obtained by Equation (4). Finally, θ_{net} is used to compute the horizontal movement of the head by Equation (5).

The values of 1.1 and 1.04 seconds used for calculating the moving average were determined to best reflect the changes in course inclination and curves through the entire timed race.

2.3. Sub-Technique Classification

The skating style sub-techniques were categorized into four gears that involve poling action: G2, G3, G4, and G6 with poling action. Techniques involving poling action that did not fit the above sub-techniques were classified as Others. G5 (skating without poles), G6 (without poling action), and G7 (downhill tuck) were not classified.

First, one poling action was defined as one cycle in each sub-technique. One poling action was extracted by classifying peaks in the net vertical movement of the head waveform. Next, the typical waveform patterns for each sub-technique were defined based on the differences in the patterns of net vertical and horizontal head movements and VOG changes within one cycle. The differences in waveform patterns were focused on the shape, amplitude, timing, and frequency of peaks and valleys. Finally, the sub-techniques during the timed race were manually (visually) classified based on the typical waveform patterns.

The validity was verified by comparing the data classified visually from video data obtained from a video camera mounted on the snowmobile with the data classified using GNSS data. Experts with over ten years of skiing experience, different from those who classified the techniques based on waveform patterns, used Kinovea video software to classify the techniques from the video data. The data classified from the video were used as the validity standard, and the consistency with the data classified from the GNSS was verified. The match rate (%) was calculated for all techniques and sub-techniques (%Match = GNSS data / Video data).

2.4. Analysis of Skiing Characteristics

The usage ratio of each sub-technique concerning time and distance during the timed race was calculated. Based on the head position data, the straight-line distance moved by the head during one cycle was calculated as CL, and the time required for one cycle was calculated as CT. Furthermore, skiing velocity was calculated by dividing CL by CT. The course inclination at which each sub-technique was used was calculated based on the difference in course incline data between one cycle's start and end points relative to CL. Using Excel statistics, a one-way analysis of variance (ANOVA) was conducted on CT, CL, skiing velocity, and course inclination for each of the two subjects. Bonferroni multiple comparisons were performed if significant variance was observed to examine the differences between the sub-techniques. The significance level was set to $\alpha = 0.05$.

3. Results

3.1. The Typical Waveform Pattern of Each Sub-Technique

The typical waveform patterns for each sub-technique were defined based on the differences in the patterns of net vertical and horizontal head movements and changes in VOG within one cycle as follows (Figure 3). G3 is characterized by a single peak or valley in the net horizontal head movement waveform within one cycle. G2 is characterized by one peak and one valley in the net horizontal head movement waveform within one cycle. Like G2, G4 has one peak and one valley in the net horizontal

head movement waveform within one cycle. However, G4 is characterized by a large wave followed by a slight wave in the net vertical head movement waveform within one cycle. G6 has the same waveform as G2 in net vertical and horizontal head movements. However, G2 and G6 can be distinguished by the following criteria. Compared to G2, G6 has a smaller amplitude in net horizontal head movement. Additionally, G6 has a higher VOG. The timing of the peaks or valleys in net horizontal head movement also differs. In G2, these are observed in the first half and middle of the cycle, whereas in G6, they appear in the middle and latter half. These typical waveform patterns for each sub-technique were observed in both subjects

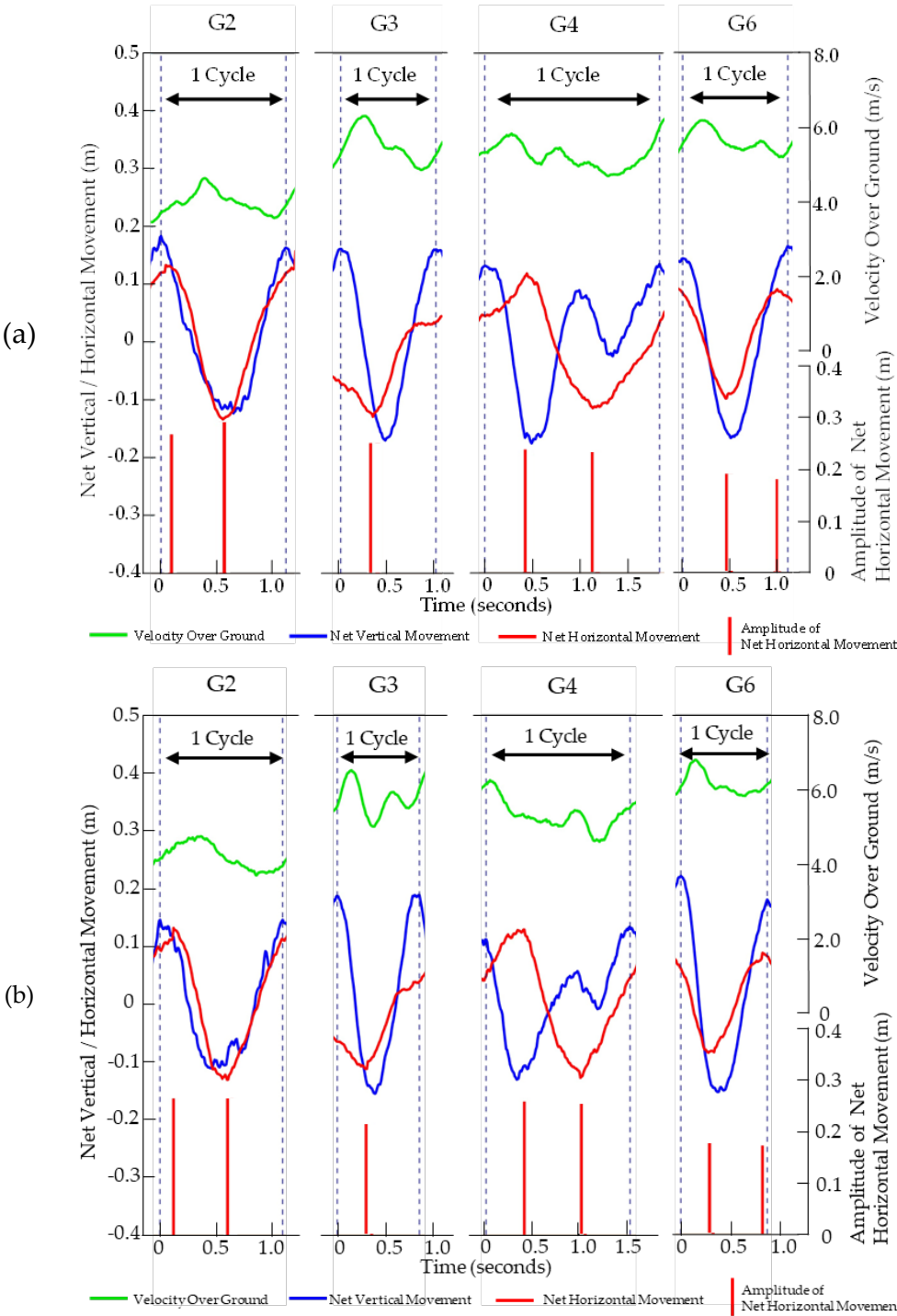


Figure 3. These figures show the typical waveform patterns of Subject A (a) and Subject B (b) for G2, G3, G4, and G6. The black dashed lines indicate the points where the net vertical head movement reaches a peak. The interval between two green lines represents one cycle. The green lines indicate

the VOG. The blue waveform shows the trajectory of the net vertical head movement. The red waveform shows the trajectory of the net horizontal head movement. The red bars indicate the amplitude of the net horizontal head movement.

3.2. Validity of Sub-Technique Classification Based on Waveform Patterns

The match rates of sub-techniques classification from video data and GNSS data were as follows: for Subject A, G2 was 99.3%, G3 was 97.7%, G4 was 98.0%, and G6 was 95.0%, with an overall match rate of 97.1% for G2, G3, G4, and G6 (Table 1a). For Subject B, G2 was 97.2%, G3 was 98.2%, G4 was 97.0%, and G6 was 94.0%, with an overall match rate of 96.5% for G2, G3, G4 and G6 (Table 1b). There was no noticeable difference in sub-technique accuracy between the two subjects.

Table 1. These tables show the consistency between classifications of subjects A (a) and B (b) using video and GNSS data.

(a)

Subject A	GNSS classification							Accuracy (%)	
	G2	G3	G4	G6	Others	None	Total		
Video classification	G2	143	0	0	1	0	0	144	99.3
	G3	0	386	2	4	2	2	396	97.5
	G4	0	0	50	0	1	0	51	98.0
	G6	0	2	2	95	0	1	100	95.0
	Others	0	0	2	1	1	0	4	25.0
	None	0	1	0	0	0	/		1
Total		143	389	56	101	4	3		

(b)

Subject B	GNSS classification							Accuracy (%)	
	G2	G3	G4	G6	Others	None	Total		
Video classification	G2	207	0	1	5	0	0	213	97.2
	G3	0	272	1	2	1	1	277	98.2
	G4	0	0	128	1	2	1	132	97.0
	G6	1	1	1	78	0	2	83	94.0
	Others	0	0	0	0	1	3	4	25.0
	None	0	0	0	1	0	/		1
Total		208	273	131	87	4	7		

3.3. Characteristics of Each Sub-Technique

The time required for the timed race was 909 seconds for Subject A and 860 seconds for Subject B. The time percentages for each technique were: G2 was 21.9% and 28.8%, G3 was 48.3% and 31.0%, G4 was 10.5% and 23.4%, G6 was 13.6% and 10.7%, and Others and G5, G6 (without poling action), G7 were 0.6% and 0.5% (Figure 4a). The distance percentages for each technique were: G2 was 16.4% and 22.8%, G3 was 47.7% and 30.5%, G4 was 12.0% and 25.5%, G6 was 14.4% and 11.5%, and Others and G5, G6 (without poling action), G7 were 0.7% and 0.5% (Figure 4b).

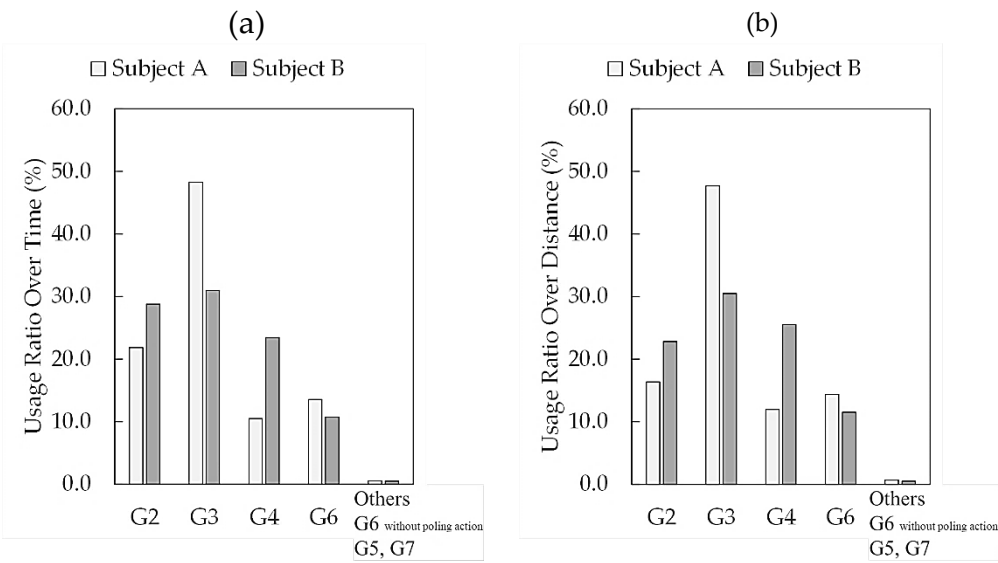


Figure 4. These figures show the usage ratio over time(a) and the ratio over distance(b) for each sub-technique during the timed race.

The sub-techniques used during the second lap of the timed race are shown on the course profile's plan view (Figure 5) and the course inclination (Figure 6). Figure 7 is the VOG of the skier's head plotted on the vertical axis.

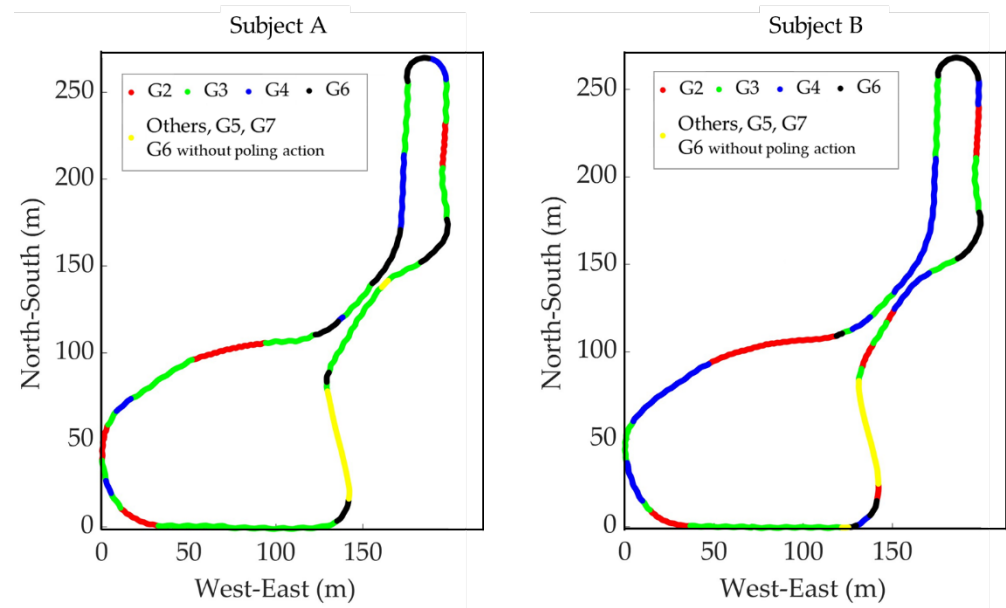


Figure 5. The distribution of sub-techniques used by two subjects during the second lap of the timed race is shown on the course profile's plan view data.

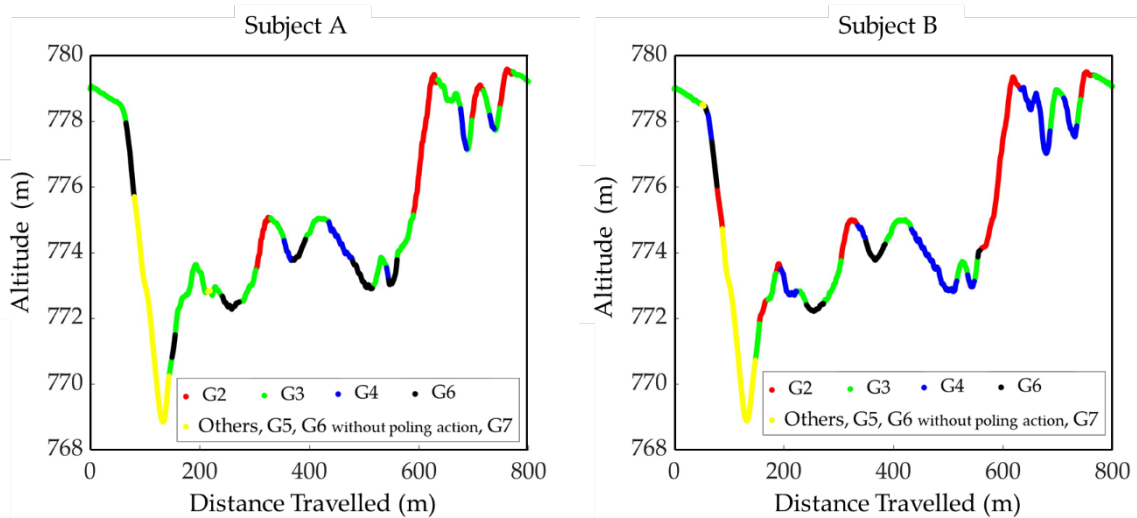


Figure 6. The course inclination data shows the distribution of sub-techniques used by two subjects during the second lap of the timed race.

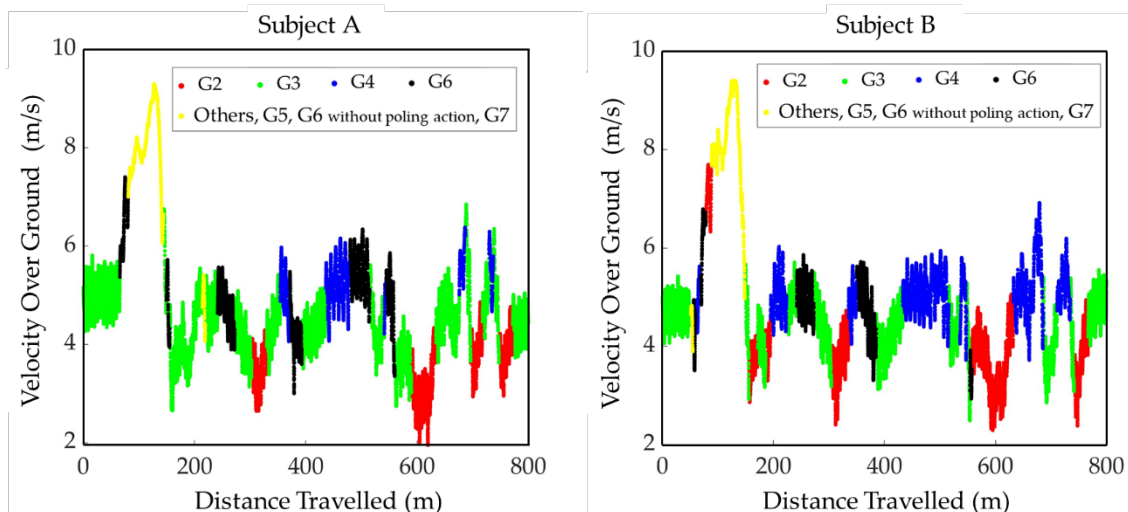


Figure 7. The distribution of sub-techniques used by two subjects during the second lap of the timed race. The X-axis indicates the distance traveled, and the Y-axis indicates the VOG of the skier's head.

The average CL for each sub-technique during the timed race for Subjects A and B were as follows (Figure 8): G2 was 4.51 ± 0.81 m and 4.32 ± 0.77 m, G3 was 4.84 ± 0.78 m and 4.40 ± 0.68 m, G4 was 8.41 ± 1.08 m and 7.68 ± 1.28 m, and G6 was 5.60 ± 1.26 m and 5.21 ± 1.05 m. The average CT were: G2 was 1.33 ± 0.09 sec and 1.15 ± 0.10 sec, G3 was 1.08 ± 0.10 sec and 0.94 ± 0.12 sec, G4 was 1.63 ± 0.17 sec and 1.49 ± 0.24 sec, and G6 was 1.17 ± 0.13 sec and 1.02 ± 0.12 sec. The average skiing velocity were: G2 was 3.38 ± 0.51 m/s and 3.77 ± 0.57 m/s, G3 was 4.45 ± 0.54 m/s and 4.69 ± 0.62 m/s, G4 was 5.15 ± 0.43 m/s and 5.18 ± 0.47 m/s, and G6 was 4.75 ± 0.71 m/s and 5.08 ± 0.75 m/s. The average course inclination for each technique was: G2 was 4.08 ± 3.20 degrees and 3.11 ± 3.40 degrees, G3 was 0.37 ± 2.50 degrees and 0.95 ± 2.74 degrees, G4 was -0.37 ± 2.50 degrees and -1.28 ± 2.36 degrees, and G6 was 0.49 ± 3.48 degrees and -0.03 ± 3.73 degrees. When comparing the CL, CT, skiing velocity, and course inclination for each sub-technique between Subjects A and B, Subject A showed significant differences in all sub-techniques except for the course inclination of G3 and G6. Subject B showed significant differences in all sub-techniques except for the CL of G2 and G3, the skiing velocity of G4 and G6, and the course inclination of G3 and G6.

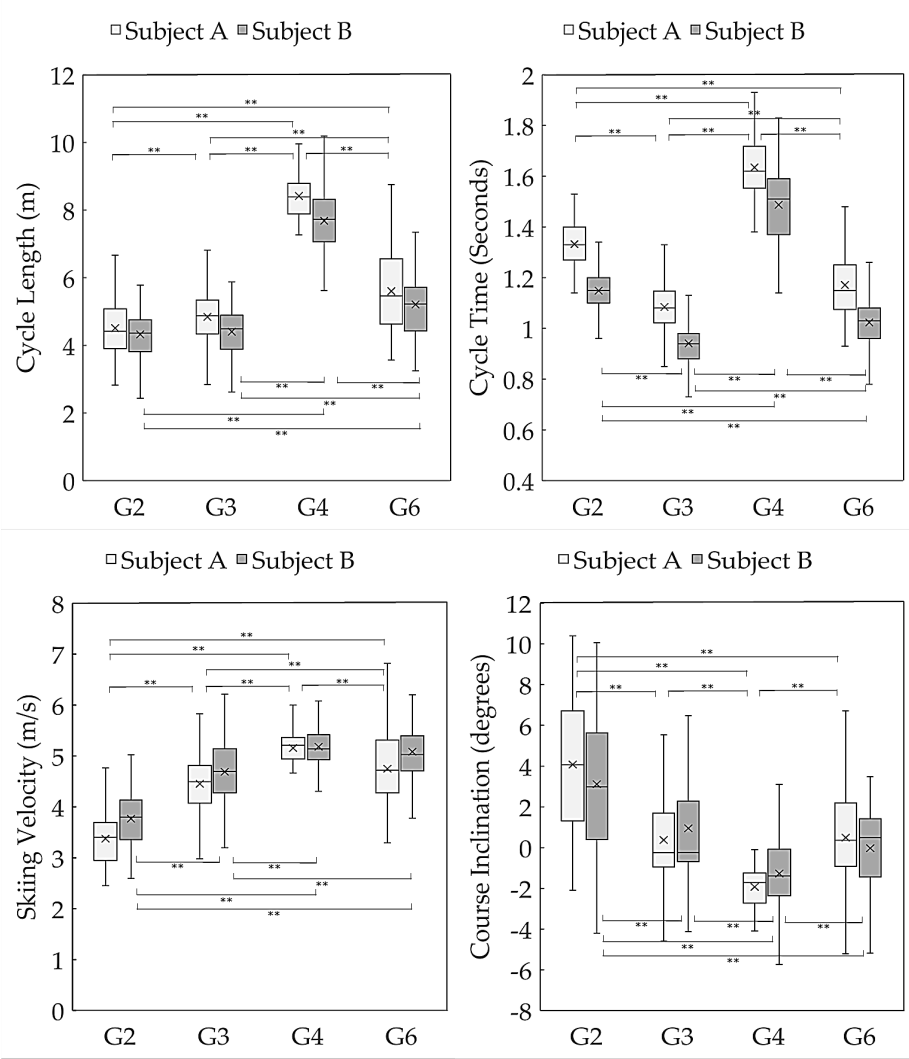


Figure 8. These figures show the CL, CT, CS, and CI data for subjects A and B sub-techniques during the trial. Each sub-technique cycle was defined from the vertical movement peak at the waveform data's head to the next peak. ** indicates a significance level of $p < 0.01$.

The distribution of four sub-techniques used by two subjects during the timed race is shown in Figures 9–11. Figure 9 shows the sub-technique distribution plotted against skiing velocity (X-axis) and course inclination (Y-axis). Figures 10 and 11 show the frequency distribution of sub-techniques as histograms for skiing velocity (Figure 10) and course inclination (Figure 11), respectively. Each sub-technique was classified and described based on GNSS data from the skier's head.

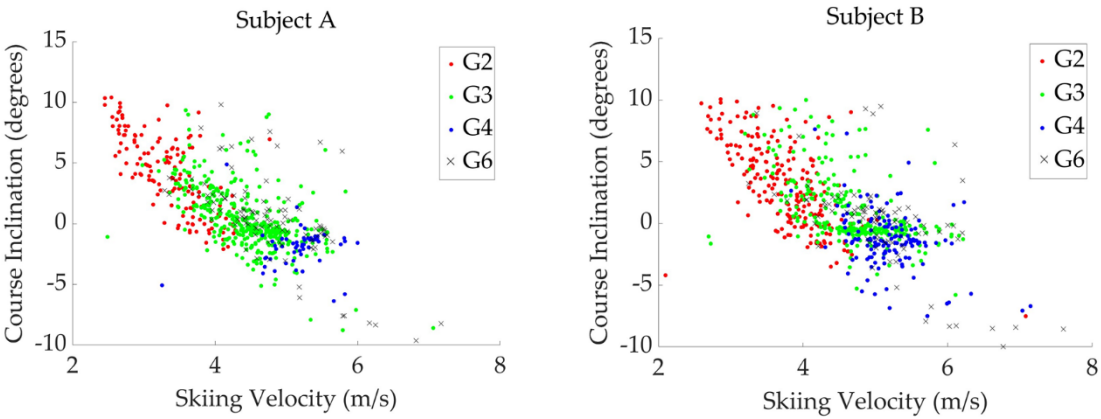


Figure 9. The distribution of four sub-techniques used by two subjects during the timed race is shown with skiing velocity (X-axis) and course inclination (Y-axis).

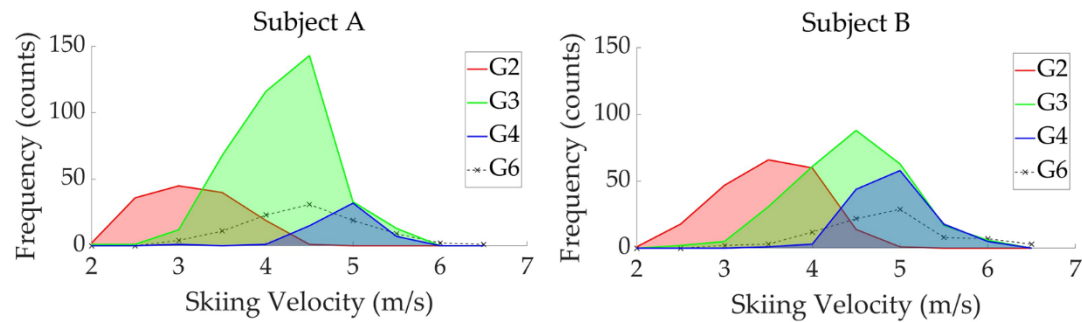


Figure 10. The distribution of four sub-techniques used by two subjects during the timed race is shown as a histogram of skiing velocity frequencies.

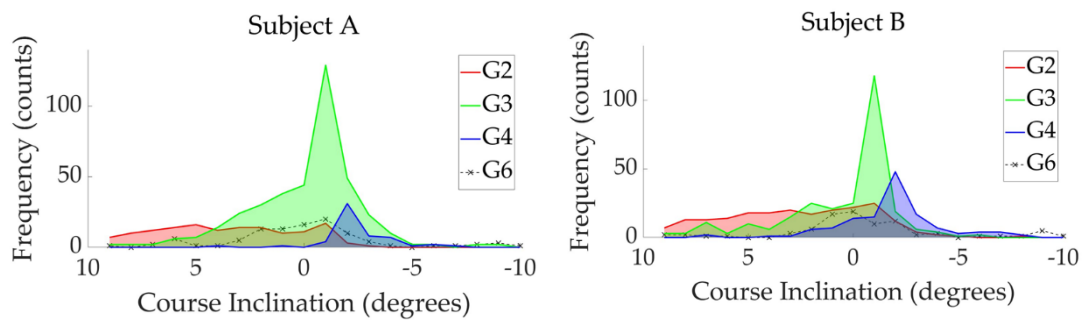


Figure 11. The distribution of four sub-techniques used by two subjects during the timed race is shown as a histogram of course inclination frequencies.

4. Discussion

This study aimed to establish a method for analyzing skating techniques on snow using a high-precision kinematic GNSS device. Based on the head movement patterns exhibited by each sub-technique, the classification accuracy was 97.0-99.3% for G2-G4 in this study. Øyvind Gløersen et al. [12] achieved 92–97% accuracy for G2-G4 in classifying sub-techniques during roller skiing. The results of our study indicated that high-accuracy classification is achievable on snow, as well as in previous studies. For G6, our study achieved an accuracy of over 94.0%, whereas the preliminary study reported an accuracy of 88%. While the preliminary study classified turns based on changes in skiing direction, we specifically focused on turns that included poling actions. Our findings demonstrate that turns involving poling actions can be accurately classified. The waveforms of vertical and horizontal head movements and VOG derived from head position data obtained from the GNSS device exhibited characteristic patterns for each sub-technique. The waveform from one peak to the next in the vertical movement represents one poling action. Peaks or valleys in the horizontal movement waveforms represent direction changes and indicate leg action. The GNSS data waveforms show that the relationship between the number of poling actions and leg actions per cycle corresponded accurately with the movements of each sub-technique demonstrated in previous studies [2,3]. For sub-techniques G2, G4, and G6 (with poling action), the relationship between the number of poling actions and leg actions within one cycle is the same. However, it was possible to classify these sub-techniques based on the timing differences of the peaks in net horizontal head movements, waveform, VOG changes, and differences in the amplitude of net horizontal movements. The waveforms of G2 and G6 (turning technique) were very similar. G2 is reflected in VOG as a slower technique because it tends to be used in areas with steeper inclines [3,15]. The differences in

the timing of horizontal movement peaks and amplitude may be influenced by G6 being a sub-technique used while turning on the course. Regarding the classification of G6, various criteria have been used, including classification based on the displacement direction ($\leq 10^\circ$) [12], including it in skating without a pole [15], and including it in G2[7]. Research focusing on G6 has mainly addressed course inclination less than 0° [16], and studies on its use in other types of terrain are still lacking. Our study reveals that G2 and G6 are sub-techniques with distinct skiing characteristics, differing in skiing velocity, CL, CT, and course inclination. Detailed analysis of G6 is also necessary to thoroughly analyze the skiing characteristics of athletes in races.

The GNSS data also revealed skiing characteristics for each sub-technique. The results showed that the ratio of each sub-technique used varied between the two subjects depending on time and distance. This suggests that the sub-techniques may differ depending on the skier's fitness and skill, even on the same course. Of the main sub-techniques for skating (G2, G3, and G4), G4 was the fastest for both subjects, followed by G3 and G2. The fact that G4 was used on the course with the most minor slope and G2 on the course with the steepest slope suggests that the course's slope influences the choice of sub-technique. Subjects A and G2 were used on the steepest sloped course. Subject A. Subject A was a former representative of Japan's national cross-country skiing team and had continued training and competing in national competitions after retiring from the national team. On the other hand, Subject B was a 15-year-old junior high school athlete, suggesting that Subject A had far greater physical strength and technique. The primary purpose of this study was to use GNSS for technique discrimination of skating technique and not to compare the technique characteristics of high-performing and non-performing athletes. However, we would like to add a few considerations to show that this study can also classify the sub-technique use ratio and technique characteristics of skiers with different skiing performances. Namely, as shown in Figures 9-11, subject A uses G3, which requires upper body strength at high speeds, even on steep slopes. This indicates that the higher-performing skier may be able to use faster techniques on the same course incline compared to less-performing skiers. Also, as shown in Figure 7, subject A used the same technique more consistently than subject B, depending on the course's slope. In contrast, subject B used multiple techniques even at the same slope, indicating that the skiers with superior performance have a higher ability to use the most appropriate technique for a given situation consistently. The results of the time race conducted in this study showed that Subject A was 49 seconds slower than Subject B. However, during the time race of Subject A, there was heavy snow in the second half of the race, and the skiing performance was inferior from the middle of the race. In addition, since the course used in this study had a relatively gentle slope, it is undeniable that the downhill skiing performance also significantly impacted the performance times. This resulted in the time of Subject A, who is supposed to have high performance, being slower than that of Subject B. This should be understood as a difficulty in experiments on snow. In any case, the authors would like to emphasize that the analysis method of this study will provide concrete suggestions for the performance and technical analysis of skiers during race.

In this study, we achieved a high-accuracy classification of skating sub-techniques and analyzed skiing characteristics on snow using a high-precision GNSS device. The strength of the high-precision GNSS device lies in its ability to provide detailed data on skiing characteristics (CL, CT, skiing velocity, course inclination, sub-technique selection) to athletes and coaches. Knowing their skiing characteristics can benefit coaches and athletes when planning race tactics. Furthermore, elucidating the relationship between these skiing characteristics and physical fitness metrics, such as upper body power and maximal oxygen uptake, can contribute to developing training goals. However, several limitations have been identified in our study. First, head position data alone cannot directly measure body rotation or center of gravity load, as can be done with sub-technique analysis based on IMU sensors [17,18]. Our analysis cannot provide detailed motion analysis of body parts as achieved with three-dimensional video analysis. Combining the analysis of the differences in head movements revealed in this study with IMU sensors and three-dimensional video analysis may allow for a more detailed examination of the athletes' technique analysis. Second, our study had a small sample size of only two subjects and relied on visual classification for the sub-technique. Increasing the number of subjects to generalize this classification method and further automating the process are challenges

for future research. Further, by transmitting GNSS data online to a smartphone or tablet and processing it using our analysis method, coaches will be able to monitor athletes' daily training data (skiing characteristics) in real-time, regardless of their location.

5. Conclusions

Based on the results of this study, it was demonstrated that by attaching a high-precision kinematic GNSS device to the skier's head during a cross-country ski skating style timed race on snow, sub-techniques can be classified based on the vertical and horizontal head movements as well as differences in VOG. Additionally, it was shown that skiing characteristics (CL, CT, skiing velocity, course inclination) can be derived from the GNSS data.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The datasets generated during and analyzed during the current study are available from the corresponding author upon reasonable request.

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