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*Technical note:*

# Inertial sensors-based estimation of temporal events in skating sub-techniques while in-field roller skiing

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# Abstract

The aim of this study was to adapt a treadmill-developed method for determination of inner-cycle parameters in cross-country roller ski skating for a field application. The method is based on detecting initial and final ground-contact of poles and skis during cyclic movements. Eleven athletes skied four laps of 2.5 km at low and high endurance-intensity, using two types of skis with different rolling coefficients. Participants were equipped with inertial measurement units (IMUs) attached to their wrists and skis, while insoles with pressure sensors and poles with force measurements were used as reference systems. The method based on IMUs was able to detect more than 97% of the temporal events compared to the reference system. The inner-cycle temporal parameters had a precision ranging from 49 to 59 ms, corresponding to 3.9% to 13.7% of the corresponding inner-cycle duration. Overall, this study showed good reliability of using IMUs on athlete's wrists and skis to determine temporal events, inner-cycle parameters and the performed sub-techniques in cross-country roller ski skating in field-conditions.


**Key words:** cross-country skiing, temporal event detection, wearable sensors, field analysis

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# Introduction:

Methods developed for laboratory settings may not be adequate for field applications or may not providing sufficient precision. Accordingly, in-field validation of such methods are required for outdoor sports such as cross-country (XC) skiing [1,2]. In outdoor skiing conditions, inertial measurement units (IMUs) and global navigation satellite system (GNSS) have shown their suitability as embedded sensors, allowing cycles and sub-technique determination [3–6]. However, such tools could also provide more detailed parameters describing the sub-techniques performed.

As a first step, we investigated the use of IMUs placed on the wrist and on the skis to detect temporal events and calculate the duration of the inner-cycle phases when roller ski skating on a treadmill [7]. The detection of the initial and final ground contact for poles and skis ($P_{ON}$, $S_{ON}$, $P_{OFF}$, $S_{OFF}$) allowed high-precision determination of the associated temporal parameters, such as cycle duration (S_CY), pole and ski contact (P_CT and S_CT) and swing time (P_SW and S_SW), as well as the type of sub-technique, expressed as gears [8]. However, whether the method can be used to obtain the same precision when roller-skiing outdoors in varied terrain using different sub-techniques must be further elucidated.

Therefore, the aim of the present study was to adapt a treadmill-developed method for determination of inner-cycle parameters in XC roller ski skating for field applications.

# Methods:

Participants: Eleven regional level skiers (9 male, 2 female), participated in the study (age 27.9 ± 6.9 years, height 180 ± 6 cm, body mass 74.2 ± 5.5 kg). The study was done in accordance with the institutional requirements and the Helsinki declaration. All skiers provided written informed consent.

Experimental setup: The protocol was performed as 4 laps of 2.5 km in a tarred loop. The participants first skied two laps at low intensity with skis equipped either with low (Type 1) or high (Type 3) friction coefficient wheels (Swenor, Sarpsborg, Norway), in a random order. Thereafter they skied two laps at high intensity with the two types of rolling resistance in a reverse order. Recovery time between laps was set to two minutes.

The skiers used poles of their individually chosen lengths, instrumented with grips measuring force at 100 Hz (Proskida, Whitehorse YT, Canada). All skiers wore their own skating XC boots, equipped with instrumented insoles measuring force at 100 Hz (Loadsol, Novel, Munich, Germany). Six IMUs (Physilog 5, GaitUp SA, Lausanne, Switzerland), each composed of a 3D accelerometer and a 3D gyroscope with a sampling frequency of 512 Hz were used to determine temporal events. Before start, the IMUs were mounted using Velcro straps on the chest, lower back, left and right wrists, and in front of the binding on both skis. A sensor including a GNSS, a 3D accelerometer and a 3D gyroscope, recording at 100 Hz was placed on the upper back using a dedicated vest (Optimeye S5, Catapult, Prahran, Australia).

Synchronization between the IMUs, the force grips, the force insole and the Catapult device was performed manually, using a dedicated pole plant followed by a jump at the beginning of each trial.

Data processing: Data from each trial were processed using a dedicated Matlab procedure (Matlab R2019a, The MathWorks Inc., Natick, Massachusetts, USA). The reference values for $P_{ON}$ and $P_{OFF}$ were obtained by the force, measured by the pole grips, using a threshold of 5% of bodyweight. The force measured by the insoles was used to determine $S_{ON}$ and $S_{OFF}$ for each ski, using a threshold of 7% of bodyweight. Inner-phases temporal parameters

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were then calculated (i.e., P_CT, P_SW, S_CT, S_SW, S_CY, delay between $P_{ON}$ and $S_{ON}$, and delay between $S_{OFF}$ and $P_{OFF}$).

To determine the events using the IMUs placed on the wrist and skis in field conditions, the method previously developed for a treadmill configuration [7] had to be adapted. However, the only major change that was required was related to $S_{OFF}$, due to the outdoor tarred road inducing more noise than the treadmill belt. To determine $S_{OFF}$ the updated method used the last negative acceleration peak of the vertical component (yaw axis) before the maximal vertical acceleration happening in the second part of the cycle.

The decision tree use in a previous study [7] to determine the sub-technique (i.e. G2-G3-G4) was adapted to include G5 (skating legs motion without poles pushes), G6 (turns) and G7 (downhill position) with no clearly defined cycle (Figure 1). The GNSS coordinates were used to determine the radius of curvature of the skier's trajectory. This radius was then used for the reference system to differentiate G6 from G5 when the skier makes steps without using the poles.

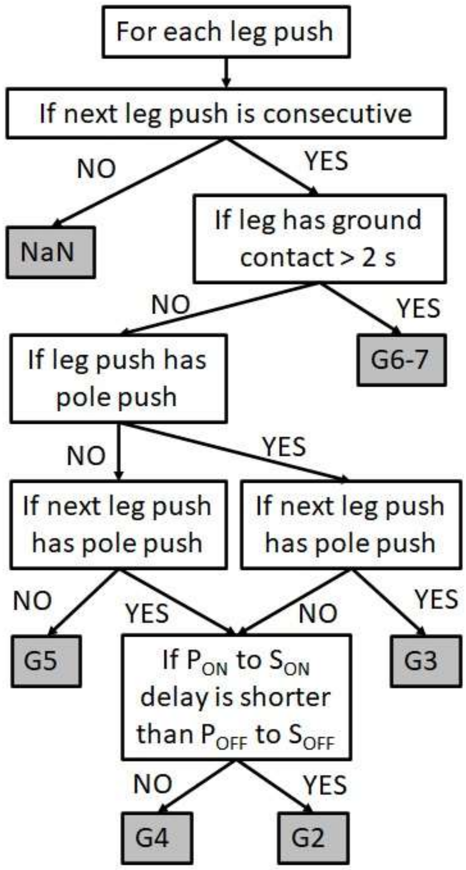


***Figure 1:*** *Decision-tree for the sub-technique determination (i.e., G2, G3, G4, G5, G6-7). NaN means undetermined category,* $P_{ON}$ *is the pole initial contact,* $P_{OFF}$ *is the pole final contact,* $S_{ON}$ *is the ski initial contact and* $S_{OFF}$ *is the ski final contact.*

Statistical analysis: For each trial, the time difference between the reference and the IMUs was computed for each cycle. The temporal parameters were compared, both in absolute and relative terms. For each parameter, the bias (intra-trial mean) and the precision (intra-trial standard deviation) were calculated for all cycles within a trial. The results from all trials were then combined to determine the overall median and interquartile range (IQR) for both the bias and the precision, resulting in four inter-trial statistics: The inter-trials median bias ($b_\mu$), the inter-trials IQR of the bias ($b_\sigma$), the inter-trials median precision ($\sigma_\mu$) and the inter-trials IQR of

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the precision ($\sigma_\sigma$) [9]. The median and IQR were used to describe the inter-trial statistics as the intra-trial bias and precision were not normally distributed.

Based on the reference system, the cycles just before and just after each transition between sub-technique were removed from the analysis.

# Results

In total, 13’038 ski cycle and 17’338 poling cycles were detected by the reference systems, and more than 97% of the temporal events were detected using the IMUs (Table 1). The assessment of the sub-technique was correct for 96.6% of the cycles (Table 1). An example of events and sub-technique determination is provided (Figure 2).

**Table 1**: Number of events determined by the force poles and insoles reference systems (REF) and the percentage (%) of correct assessment by the inertial measurement units, for the different sub-techniques (G2-G5).

| | G2 | | G3 | | G4 | | G5 | | All Gear | |
|---|---|---|---|---|---|---|---|---|---|---|
| | REF | % | REF | % | REF | % | REF | % | REF | % |
| Pole initial contact | 6283 | 97.9 | 10426 | 97.9 | 629 | 98.6 | | | 17338 | 97.9 |
| Pole final contact | 6283 | 97.5 | 10426 | 97.1 | 629 | 94.8 | | | 17338 | 97.1 |
| Ski initial contact | 6369 | 98.5 | 5382 | 97.7 | 720 | 99.2 | 567 | 88.2 | 13038 | 97.8 |
| Ski final contact | 6369 | 98.2 | 5382 | 98.1 | 720 | 97.6 | 567 | 91.5 | 13038 | 97.8 |
| Sub-technique | 6274 | 97.1 | 5259 | 97.9 | 714 | 92.6 | 500 | 83.2 | 12747 | 96.6 |

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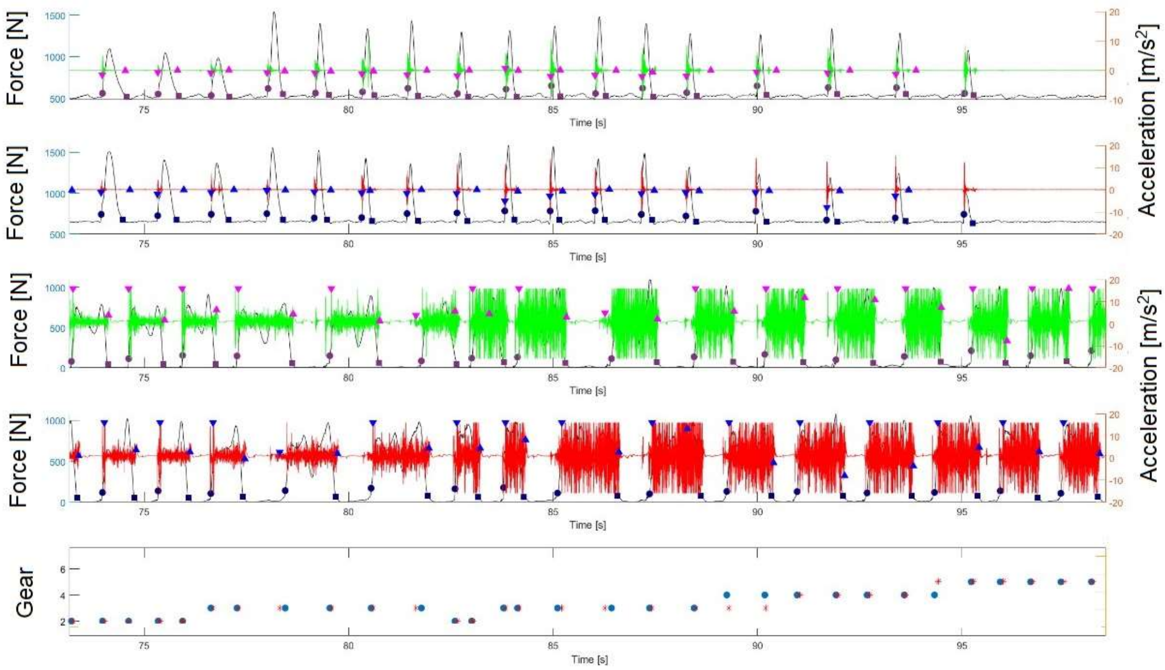


***Figure 2:*** *Events detection for the poles (top two graphs) and the skis (third and fourth graphs). The black curves are the forces from the reference system, ● indicate initial contact and ■ indicate final contact. The green curves are used for left and red curves for right for the Inertial measurement units (IMU), ▲and ▼indicate initial contact and final contact respectively. The lower graph shows the gear determination for the reference (●) and the IMUs (*).*

The bias $b_\mu$ obtained for the poles and skis initial and final contact ranged between 21 ms and 65 ms. For the inner-cycle parameters, the precision $\sigma_\mu$, ranged between 15 ms and 69 ms. Relatively to the corresponding phase duration, the temporal parameters associated with the skis achieved a precision between 3.9% and 8.6%, while the parameters associated with the poles ranged between 8.7% and 13.7% (Table 2).

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**Table 2**: Time differences between the temporal events determined using the reference system (force poles and insoles) and using inertial measurement units, as well as for the inner-cycle parameters of the different sub-techniques (G2-G5).

| | G2 | | | | G3 | | | | G4 | | | | G5 | | | | All Gear | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $b_\mu$ | $b_\sigma$ | $\sigma_\mu$ | $\sigma_\sigma$ | $b_\mu$ | $b_\sigma$ | $\sigma_\mu$ | $\sigma_\sigma$ | $b_\mu$ | $b_\sigma$ | $\sigma_\mu$ | $\sigma_\sigma$ | $b_\mu$ | $b_\sigma$ | $\sigma_\mu$ | $\sigma_\sigma$ | $b_\mu$ | $b_\sigma$ | $\sigma_\mu$ | $\sigma_\sigma$ |
| Pole initial contact ($P_{ON}$) | -7 | 22 | 17 | 9 | -7 | 21 | 20 | 9 | -17 | 28 | 12 | 13 | | | | | -8 | 23 | 20 | 8 |
| Pole final contact ($P_{OFF}$) | -26 | 65 | 56 | 23 | -16 | 39 | 44 | 27 | -38 | 63 | 25 | 51 | | | | | -16 | 50 | 59 | 19 |
| Ski initial contact ($S_{ON}$) | -23 | 23 | 42 | 20 | -2 | 32 | 57 | 18 | -16 | 37 | 46 | 31 | -41 | 55 | 51 | 52 | -14 | 31 | 55 | 13 |
| Ski final contact ($S_{OFF}$) | -15 | 30 | 20 | 10 | -17 | 30 | 23 | 8 | -13 | 37 | 19 | 31 | -28 | 32 | 22 | 22 | -15 | 30 | 28 | 9 |
| Pole contact time | -13 | 67 | 57 | 22 | -6 | 38 | 40 | 32 | -18 | 52 | 17 | 49 | | | | | -8 | 38 | 58 | 23 |
| Pole swing time | 22 | 67 | 59 | 28 | 15 | 39 | 40 | 31 | 29 | 54 | 15 | 48 | | | | | 17 | 39 | 57 | 23 |
| Ski contact time | 5 | 11 | 37 | 22 | -9 | 33 | 55 | 17 | 0 | 31 | 51 | 43 | 12 | 32 | 52 | 66 | -1 | 19 | 49 | 12 |
| Ski swing time | 1 | 12 | 37 | 21 | 18 | 36 | 53 | 16 | 4 | 41 | 51 | 45 | -3 | 35 | 52 | 43 | 8 | 19 | 50 | 14 |
| Ski cycle time | 0 | 2 | 37 | 31 | -2 | 4 | 69 | 22 | 0 | 18 | 61 | 39 | -3 | 23 | 68 | 47 | -1 | 3 | 59 | 15 |
| Pole contact time % | -2.5 | 10.9 | 9.8 | 4.2 | -1.4 | 10.9 | 13.5 | 8.2 | -6.6 | 18.7 | 6.7 | 17.9 | | | | | -2.6 | 9.1 | 13.7 | 7.6 |
| Pole swing time % | 3.1 | 9.7 | 8.3 | 3.8 | 2.0 | 6.2 | 6.5 | 5.4 | 2.0 | 3.9 | 1.1 | 3.4 | | | | | 2.2 | 5.6 | 8.7 | 3.5 |
| Ski contact time % | 0.7 | 1.4 | 4.8 | 3.1 | -0.7 | 3.0 | 5.3 | 1.7 | 0.0 | 3.4 | 5.4 | 5.2 | 1.6 | 3.2 | 5.6 | 6.9 | -0.1 | 2.0 | 5.9 | 2.1 |
| Ski swing time % | 0.1 | 2.7 | 7.5 | 4.5 | 2.1 | 4.0 | 8.1 | 2.8 | 0.3 | 5.8 | 7.0 | 7.7 | -0.3 | 5.7 | 8.3 | 4.8 | 0.8 | 2.5 | 8.6 | 3.4 |
| Ski cycle time % | 0.0 | 0.1 | 3.2 | 1.9 | -0.2 | 0.3 | 3.8 | 1.2 | 0.0 | 1.1 | 3.8 | 2.6 | 0.0 | 1.5 | 4.5 | 3.4 | -0.1 | 0.2 | 3.9 | 1.2 |

Time differences are expressed in milliseconds (ms) and in percentage of the inner-cycle phase duration. A positive difference indicates that the event was detected earlier on the IMU data than on the reference. " b" and " σ" are the abbreviations for bias (intra-trial mean error) and precision (intra-trial standard deviation of the error), respectively, while subscript " μ" and " σ" represent the median and the interquartile range over all the trials.

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# Discussion

This is the first validation-study for the use of IMUs placed on the athlete and equipment to determine inner-cycle temporal parameters in XC roller ski skating in the field. More than 97% of the temporal events were detected and the deduced inner-cycle parameters were calculated with an average precision between 49 and 59 ms (3.9-13.7% of the corresponding phase duration). The precision is a bit lower than previously obtained in a laboratory setting were 99% of the events were detected and the inner-cycles parameters were calculated with an average precision between 19 and 66 ms [7]. $P_{OFF}$ was a bit more difficult to assess in the field, probably because the pole tips sometimes slip at the end of the poling phase.

In our study, the precision in absolute terms is similarly high for P_CT, P_SW, S_CT and S_SW. In terms of relative error, P_CT obtained the lowest precision (13.7%), as this phase has the shortest duration (i.e., approximately half of the P_SW). Here, detecting and removing $P_{OFF}$, where the poles are skidding, could improve the accuracy of the method. Then, the detection algorithm could be further improved by using different scenarios to detect $P_{OFF}$, since speed, slope, used sub-technique, and the different athletes' technique can affect the sensors outcome. Nevertheless, the precision reached in this study is similar to previously published results in both the classical [10] and skating styles [6]. It is also expected to get similar or even better results on snow, since the pole tip grips better on snow then asphalt, and snow will reduce vibrations [11].

The determination of the sub-technique using the temporal events and a decision tree provided good results. The results obtained can be compared to the ones obtained with machine learning in the classical style [12] or using a similar decision tree in roller ski skating [4]. The common issue that prevents us from reaching an even better sub-technique determination is to recognise the turns and the transitions between sub-techniques.

Overall, this study showed good precision when using IMUs on athlete's wrists and skis to determine temporal events, inner-cycle parameters and the performed sub-techniques in XC roller skating in field-conditions.

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