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Temporal and kinematic patterns distinguishing the G2 from the G4 skating sub-technique

F. Meyer[a], J. Kocbach[b], J. Tjønnås[c], J. Danielsen[b], T. M. Seeberg[d], A. Austeng[a] and Ø. Sandbakk[b]

[a]Department of Informatics, Digital Signal Processing Group, University of Oslo, Oslo, Norway; [b]Department of Neuromedicine and Movement Science, Centre for Elite Sports Research, Norwegian University of Science and Technology, Trondheim, Norway; [c]Mathematics and Cybernetics, SINTEF Digital, Oslo, Norway; [d]Smart Sensor Systems, SINTEF Digital, Oslo, Norway

ABSTRACT

In cross-country ski skating, both the G2 and G4 sub-techniques involve one pole push for every second ski push but are used at largely different speed-slope ranges. The aim of this study was to compare temporal and kinematic patterns between G2 and G4 at both identical and different speed-slope conditions. A mixed model was used to analyse spatio-temporal parameters, while a combination of dynamic time warping and statistical parametric mapping was used to compare time traces. Main spatio-temporal parameters, such as cycle time, ski contact time and swing time, differed between G2 and G4 (all $p < 0.01$). Moreover, two forward and more pronounced acceleration phases of the centre of mass (CoM) were visible in G4 while only one acceleration phase was present in G2. The more continuous propulsion in G2 allows for maintaining a more constant speed at steep slopes and low speeds where this sub-technique is preferred. In contrast, the achievement of high speeds while skiing on flatter terrain seem to require more dynamic motion with shorter, more explosive propulsion periods allowed for in G4. In conclusion, G2 and G4 are two unique movements as characterised by fundamentally different CoM motion and should be denoted as two different sub-techniques.

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KEYWORDS
Kinematic; motion analysis; centre of mass; dynamic time warping; statistical parametric mapping; roller skiing; cross country skiing

Introduction

Cross-country (XC) skiing involves two main styles, classical and skating, with different sub-techniques that athletes change between in order to optimise their skiing efficiency across the varying skiing speeds and terrains (Sandbakk & Holmberg, 2017). Both during on-snow and roller ski skating, these sub-techniques are designated as gears (G) from one to seven (Nilsson et al., 2004). In contrast to the classical style sub-techniques, the skis in skating are gliding forward on the snow in a zig-zag motion. The only way the skier can generate propulsive ski force on a forward-gliding ski is to apply ski force perpendicular to the ski gliding direction. Thus, in contrast to classical

CONTACT F. Meyer fredem@uio.no

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XC skiing, the ski push-off in skating XC skiing is essentially unrestricted by skiing speed, similar to speed skating (De Boer et al., 1987). On the other hand, pole propulsion times will in both styles and in all sub-techniques be more or less restricted by skiing speed. That is, the higher the skiing speed, the shorter the pole propulsion time, although pole (and ski) propulsion times can be adjusted quite considerably within each sub-technique.

The main sub-techniques employed in skating are G2, G3 and G4 (Figure 1) (Andersson et al., 2010). In normal continuous skiing in undulating terrain, G2 is normally used for skiing uphill at low speeds, involving an asymmetrical double pole push in connection with every other leg push. At moderate slopes and intermediate speeds, G3 is normally used and involves one synchronised double pole push together with every leg push. With a further increase in speed and/or reduction in slope, skiers normally use G4, which is similar to G2 because it also involves one double poling action with every other leg push. However, the double poling action in G4 is more symmetrical than in G2 (Bilodeau et al., 1996; Nilsson et al., 2004).

Recently, Herzog et al. (2015) showed that these transitions between sub-techniques indeed occur. However, since both G2 and G4 have only one pole push for every second leg/ski push, they characterised both G2 and G4 as the same sub-technique, labelled 2-skate. Obviously, confusion exist in the literature regarding the possible similarities and differences between G2 and G4. One possible way of comparing these two sub-techniques is by examining the trajectory of the centre of mass (CoM) as done previously for other types of human locomotion. For example, the most used definition separating walking from running is the trajectory of the body's centre of mass in the vertical plane (Cavagna et al., 1977). In walking, the CoM reaches its maximum (highest value) during midstance,

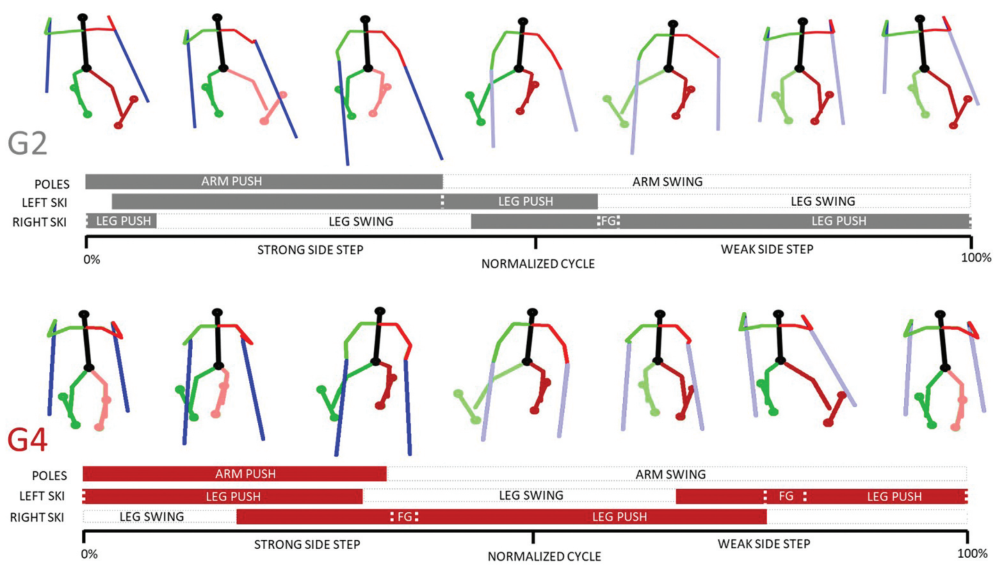

Figure 1. Cycle definition for both G2 and G4 skating sub-technique. The cycle starts when the left pole touches the ground and is normalised over time. Stick figure are plotted from tri-dimensional data using a posterior view of the skier. FG represents the free gliding phases. Dark colour shading represents segments in contact with the ground.

while in running the CoM reaches its minimum (lowest value) during midstance. Such fundamental mechanisms likely differ between G2 and G4, and will probably relate to their specific advantages in clearly different conditions.

In uphill skiing, where a large component of gravity is acting along the slope, the skier usually choose a movement pattern characterised by small velocity fluctuations (Dahl et al., 2017). Since the speed is usually low at steeper inclines, a long pole propulsion time can be achieved, which together with relatively constant pushes with the skis/legs in G2 aids in keeping velocity fluctuations small. In contrast, G4 is used at relatively flat terrain at which deceleration due to gravity (component of gravity acting along the slope) is small or non-existent. Accordingly, speed loss is smaller during the non-propulsion phases in more flat terrain. Hence, the need for continuous propulsion in G4 is likely less important than in G2. However, the faster speeds typically involved when G4 is used, usually means shorter poling times, similar to high-speed double poling in classic. In double poling, the skier adapts a movement pattern characterised by a large vertical CoM amplitude, allowing the legs to contribute in generating large pole force over such short poling times (Danielsen et al., 2018; Holmberg et al., 2006, 2005; Lindinger et al., 2008).

Taken together, the fundamental locomotion mechanisms differentiating the G2 and G4 sub-techniques presented in the current literature is not clear. It can be expected that G2 and G4 rely on fundamentally different locomotion mechanisms, similar to the case between walking and running (Cavagna et al., 1977), or diagonal stride versus walking and running (Kehler et al., 2014). Although Lindinger (2006) described the motion of the CoM in G2 and G4, they did not compare the techniques directly under standardised conditions. Moreover, it is not clear how the possible differences between G2 and G4 would be influenced by condition, i.e., from being compared at identical speed-incline combinations well-suited for both G2 and G4 to being employed at the preferred conditions for each of the sub-techniques. Accordingly, the aim of this study was to compare temporal and kinematic patterns between G2 and G4 at both identical and different speed-slope conditions. We hypothesised that G2 and G4 would induce clearly different motion patterns and higher CoM acceleration amplitude in G4 compared to G2, even at an identical slope and incline. This would highlight the characteristics of two different sub-techniques adapted to different conditions.

Methods

Participants

Thirteen well-trained male athletes, consisting of eight cross-country skiers (International Ski Federation distance points: 47.3 ± 20.9), and five national level biathletes participated in this experiment. The participant characteristics were as following: ages of 24.8 ± 2.7 years, body heights of 184 ± 6 cm, body masses of 79.3 ± 5.2 kg and peak oxygen uptakes of 69 ± 3.7 $mL{\cdot}min^{-1}{\cdot}kg^{-1}$. The study was approved by the local ethic committee and performed according to the Declaration of Helsinki. All participants were fully informed of its nature before providing their written consent to participate.

Equipment

The protocol was performed on a 3-by-5-m motor-driven rollerski treadmill (Forcelink S-mill, Motekforce Link, Amsterdam, The Netherlands). The skiers used poles of their individually chosen lengths of 90 ± 2% of body height. All skiers wore their own skating cross-country skiing shoes but used the same pair of skate elite roller skis (IDT Sports, Lena, Norway) with an NNN-binding system (Rottefella, Klokkarstua, Norway) and with standard category 2 wheels to minimise variations in roller resistance. The rolling friction coefficient (μ) was tested before, at various times during, and after the study, using a towing test method (Sandbakk et al., 2010), providing an average μ-value of 0.016 and no significant change over the study. Slope and speed of the treadmill were calibrated before and after the study using the Qualisys system (Qualisys AB, Gothenburg, Sweden). The visual movement of the skiers was captured from behind with a video camera (GoPro Hero6, Inc, San Mateo, CA). Participants wore a safety harness connected to an automatic emergency brake during the high-intensity parts of the tests.

Motion data were collected by using eight Oqus 400 infrared cameras (Qualisys AB, Gothenburg, Sweden), capturing three-dimensional position characteristics of passive reflective markers placed bi-laterally on the following anatomical landmarks of the body: the fifth metatarsal of the foot (on the ski boot), the lateral malleolus at the ankle (on the ski boot), the lateral femoral epicondyle, the greater trochanter, the lateral end of the acromion process, the lateral humeral epicondyle and the ulnar styloid process. These landmarks defined the endpoints of 12 body segments. Markers placed on the lateral sides of the carbide pole tips and on the lateral sides of the poles ~10 cm below the pole handles, as well as two markers at the front and back of each ski, tracked position of the skis and poles.

Procedures

The protocol was held on two consecutive testing days and was part of a more extensive study (Seeberg et al., 2021). Both test-days started with five minutes of standardised low intensity warm-up on the treadmill at constant speed. On the first test day, each skier performed twelve randomised stages of four minutes exercise with constant speed and slope, using the G2 at 12% slope (6, 7, 8, 9 km·h^{-1}), G3 at 5% slope (10, 12, 14, 16 km·h^{-1}) and G4 at 2% slope (15, 18, 21, 24 km·h^{-1}). A minimum of two minutes of recovery was given between each bout. In the current study, G2 at 7 km·h^{-1} and G4 at 21 km·h^{-1} were included as they correspond to the same intensity than the 8%, 10 km·h^{-1} condition (Seeberg et al., 2021). On the second test day, the protocol included two trials of four minutes exercise using G2 and G4 at the same slope/speed combination (8% slope, 10 km·h^{-1}).

Data processing

Each trial was processed using a dedicated Matlab procedure (Matlab R2019a, The MathWorks Inc., Natick, Massachusetts, USA). Three-dimensional trajectories of the markers were first filtered using a 10 Hz low pass Butterworth filter. The CoM of the body was then calculated by determining the CoM of each segment and assigning relative weight using the Zatsiorsky model (Zatsiorsky & Seluyanov, 1983). It has been shown that the accuracy of the CoM position calculation is less than 1% of the participant's height (Virmavirta & Isolehto, 2014). In our case, the trunk was defined by the two greater trochanter and the two acromion's markers. As no markers were placed on the head, we assumed a neutral position of the head relative to the trunk and assigned the weight of the head to the mean of the two acromion's positions. Skiing cycles were defined as proposed by Andersson et al. (2010), starting when the left pole hits the ground. Pole and ski on (ON) and off from the ground (OF) were determined by first preselecting sections where the poles and skis were close to the treadmill, and then using the maximum of the second derivative of the vertical position of each pole and each ski. The following spatio-temporal parameters were then calculated using poles and ski ON and OF: Ski contact time, ski swing time, step time (time between ON of left and ON of right ski), cycle time, skis double contact time (when the two skis are simultaneously in contact of the ground), poling time, pole swing time, delay between left pole ON and right pole ON, the absolute value of the shortest delay between skis ON and pole ON, the absolute value of the shortest delay between ski OF and pole OF. The angle between skis was calculated using the average ski orientation during the ski contact time. Shoulder rotation was defined as the maximum rotation of the shoulders in the horizontal plane during the cycle and calculated using the orientation of the segment defined by the left and right acromion. CoM lateral amplitude and CoM vertical amplitude were defined as the maximum amplitude in the corresponding axis during the cycle. The CoM forward speed amplitude was also computed as the difference between the minimum and maximal forward speed of the CoM. The free gliding phase (no pole or ski propulsion) was determined as the time periods where the real forward acceleration (realXacc) was negative and calculated as the sum of the CoM forward acceleration, the acceleration due to the roller ski friction, and the acceleration due to gravity:

$$realXacc = COMx_{Acc} + \mu \cdot g \cdot \cos(\alpha) + g \cdot \sin(\alpha) \tag{1}$$

The skis push time was defined as the time periods where the poles were not in contact with the ground and the ski were not in free glide. Finally, important temporal parameters were also expressed relative to the stride cycle duration.

Statistical analyses

A linear mixed model was applied to compare spatio-temporal parameters of first G2 8% and G4 8%, with Gear (G2 vs G4) modelled as fixed effect, while participants were used as random effect (intercept). These statistical comparisons were obtained using Jamovi Software (Jamovi project 2020, Version 1.2). Pseudo-R^2, Fischer F-values and p-values were determined (Johnson, 2014). All data are presented as mean ± standard deviation (SD). For all statistical analyses, significance was accepted at $p < 0.05$. Thresholds used for small, moderate, large, very large, and extremely large R^2 coefficients were 0.1, 0.3, 0.5, 0.7, and 0.9, respectively (Hopkins et al., 2009).

For each condition, time traces representing the CoM forward, lateral and vertical acceleration, as well as forward acceleration of the arms were compared using a two-step process. First, dynamic time warping (DTW) (Sakoe & Chiba, 1978) was used to remove temporal misalignment of the two compared signal, within a 15% limit. This means that delays up to 15% of the relative cycle duration were removed. The second step consisted in applying statistical parametric mapping (SPM) (Pataky et al., 2015) on the resulting curves to determine parts of the cycle with significantly different behaviour. For the CoM acceleration analysis, the start of the cycle was defined at the ON of the strong ski, as lateral and vertical motion of the CoM are mainly related to leg behaviour. For the forward acceleration of the arms, the start of the cycle was defined at the ON of the left pole.

Results

The comparison of spatio-temporal parameters obtained for G2 and G4 performed at the same slope (8%) and speed (10 km·h^{-1}), with the corresponding statistical analyses, are presented in Table 1. The spatio-temporal parameters in absolute terms were different, with large to extremely large effect sizes (i.e.,: the ski contact time, ski swing time, cycle time, pole swing time, free glide time, angle between skis, shoulders rotation, CoM lateral and vertical amplitude, as well as CoM forward speed amplitude). Only the poling time and the poles delay at ON did not significantly differ between G2 and G4. For spatio-temporal parameters relative to the cycle duration, the relative poling time, relative pole swing time and relative free glide time were significantly different between G2 and G4, while the relative ski contact and ski swing times were not different. Table S1 in supplementary material provides a detailed description of all the spatio-temporal parameters calculated for the four conditions.

The evolution of the forward speed (Figure 2(a)) and acceleration (Figure (2b)) of the arms for G2 and G4 showed a similar pattern, even though the curves are a bit shifted, with G2 values reaching G4 values with a small delay at the same slope and speed. G4 at the 2% slope was even more shifted, with an early negative peak in the speed and acceleration of the arms. G2 at 12% followed a very similar curve as G2 at 8%. This

Table 1. Comparison of the spatio-temporal parameters calculated for G2 and G4 at the same slope and speed, in both absolute and relative terms (in percent of the stride cycle duration), with the corresponding R^2 coefficient, F-value and P-value.

	G4			G2			G2 vs G4		
	8%, 10 Km/h			8%, 10 Km/h			R^2	F	P
Ski contact time (s)	0.98	±	0.06	0.84	±	0.06	0.91	207.8	<.001
Ski swing time (s)	0.69	±	0.05	0.60	±	0.05	0.86	82.2	<.001
Cycle time (s)	1.66	±	0.08	1.43	±	0.09	0.83	78.8	<.001
Poling time (s)	0.53	±	0.06	0.61	±	0.08	0.59	4.4	0.06
Pole swing time (s)	1.09	±	0.06	0.82	±	0.11	0.69	45.7	<.001
Poles delay (s)	0.01	±	0.00	0.03	±	0.04	0.20	2.4	0.15
Free glide time (s)	0.07	±	0.03	0.01	±	0.02	0.80	68.4	<.001
Angle between skis (°)	29.63	±	3.61	33.82	±	2.65	0.61	32.0	<.001
Shoulders rotation (°)	11.18	±	2.76	17.47	±	3.71	0.74	41.0	<.001
COM lateral amp. (m)	0.36	±	0.02	0.28	±	0.03	0.64	37.0	<.001
COM vertical amp. (m)	0.14	±	0.01	0.09	±	0.02	0.78	69.2	<.001
COM forward speed amp. (m·s^{-1})	0.52	±	0.08	0.34	±	0.04	0.89	117.0	<.001
Relative ski contact time (%)	0.59	±	0.02	0.58	±	0.02	0.14	0.20	0.63
Relative ski swing time (%)	0.41	±	0.03	0.42	±	0.02	0.14	0.10	0.73
Relative pole contact time (%)	0.32	±	0.03	0.43	±	0.06	0.72	35.00	<.001
Relative pole swing time (%)	0.66	±	0.03	0.57	±	0.06	0.33	7.83	<.001
Relative free glide time (%)	0.05	±	0.01	0.01	±	0.01	0.62	35.4	<.001

Linear mixed model with a fixed effect on gear and a random effect on intercept.
Centre of mass (COM), Gear 2 (G2), Gear 4 (G4), amplitude (amp.)
Values are given as mean ± SD.

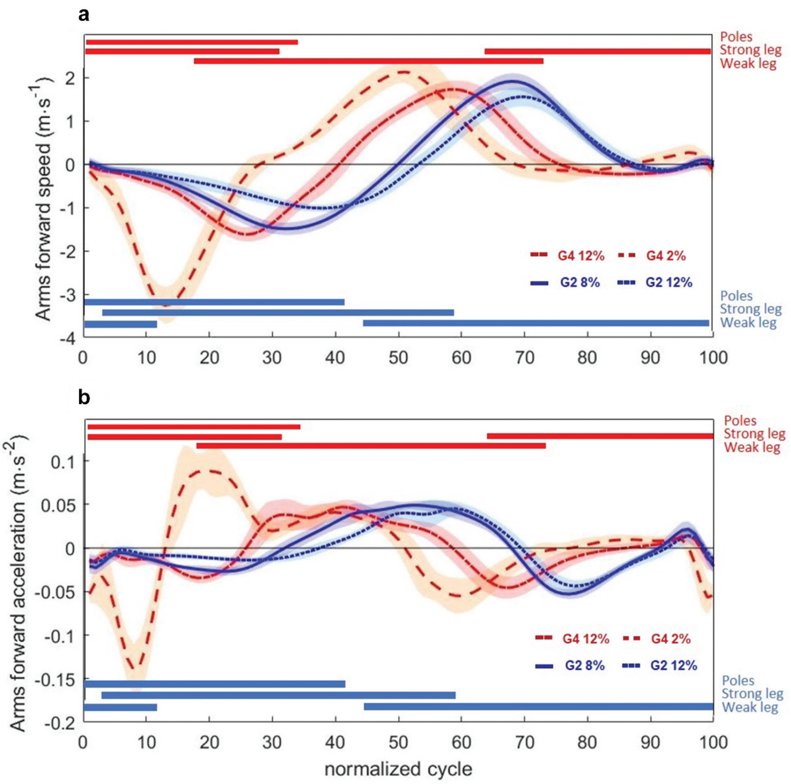

Figure 2. (a) Arms forward speed relative to the average cycle speed and (b) The arms forward acceleration. Gear 4 (G4) at 8% slope is represented in dash-dot red lines, G4 at 2% slope in dashed red lines, gear 2 (G2) at 8% slope in solid blue lines, and G2 at 12% slope in dotted blue lines. Upper (red) and lower (blue) horizontal bars in represent the phases of contact for poles, strong side ski and weak side ski during the stride cycle for G4 and G2, respectively.

was confirmed by the SPM analysis (Figure 3(a-c)), with no clear differences between the conditions once the timing was corrected for.

The CoM forward speed (Figure 4(a)) and acceleration (Figure 4(b)) curves for G2 and G4 highlighted different patterns in the CoM acceleration, with only one peak in G2 and two in G4. The G4 at 8% showed a main acceleration peak associated with the pole push, and a lower peak on the second half of the cycle. In contrast, the two G2 conditions were very similar. These observations were confirmed by the SMP analysis. After an initially higher peak in G4, a second peak was visible also for G4 at approximately 60% of the cycle (Figure 5(a)). Then, G4 at 8% showed a higher first peak than G4 at 2%, but also two more pronounced deceleration peaks (Figure 5(b)). Finally, G2 did not show any difference on the SPM analysis when comparing the 8% and the 12% slope.

The CoM lateral speed (Figure 6(a)) and acceleration (Figure 6(b)) highlighted a longer time spent on the strong side in G4 compared to G2, but the SPM analysis of the CoM lateral acceleration provided a very similar pattern between G2 and G4 (Figure 7(a-c)).

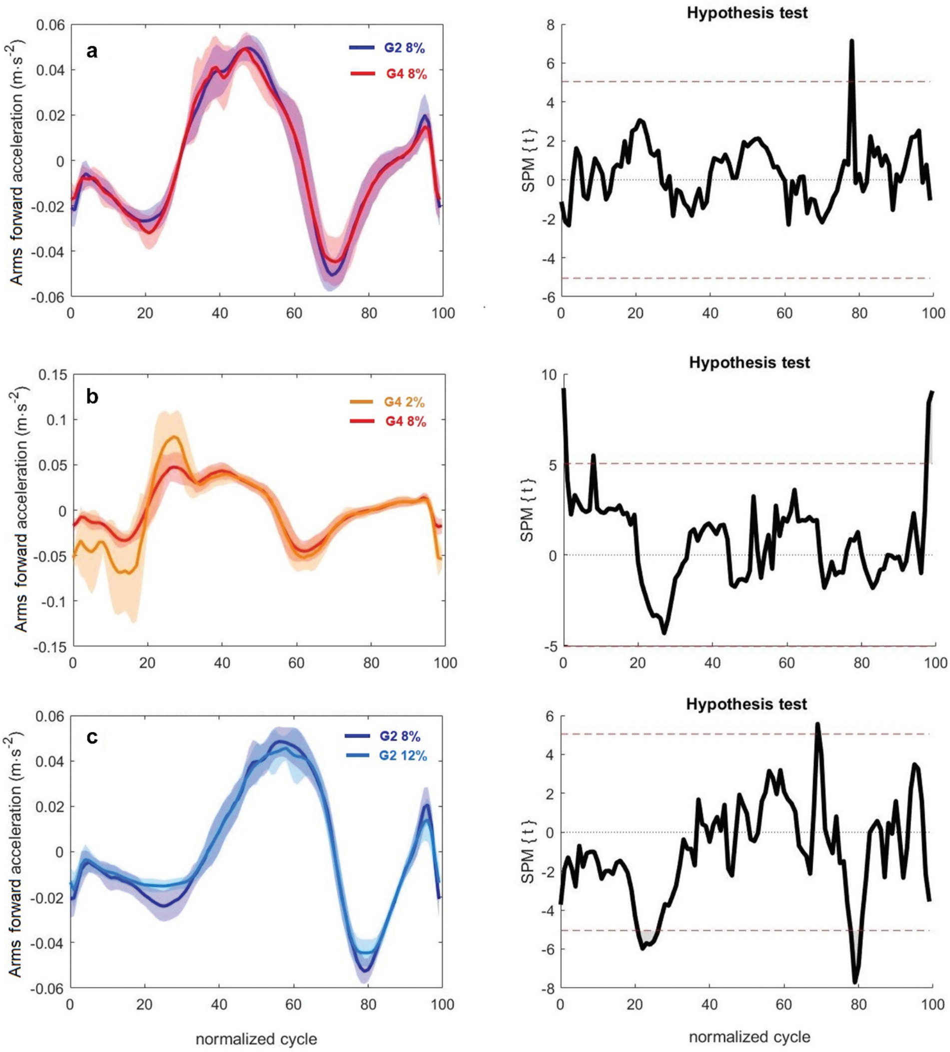

Figure 3. Dynamic time warping (DTW) applied to the arms forward acceleration relative to the average cycle speed, on the left-hand side, and the corresponding statistical parametric mapping (SPM) on the right and side. (a) Comparison of G4 in red and G2 in blue at 8% slope; (b) Comparison of G4 at 8% slope in red and G4 at 2% slope in orange; (c) Comparison of G2 at 8% slope in blue and G2 at 12% slope in light blue.

Finally, the CoM vertical speed (Figure 8(a)) and acceleration (Figure 8(b)) also showed clear differences between G2 and G4, with two positive and two negative acceleration peaks of the CoM in G4 and a much smaller amplitude of the first negative deceleration peak in G2. When adjusting for timing, the SPM analysis of the vertical acceleration of the CoM confirmed a higher CoM vertical acceleration amplitude on both the weak and the strong side in G4 (Figure 9(a)). Comparing G4 at 2% and 8% slope showed no significant differences in the vertical acceleration of the CoM at the speeds investigated here, which was also the case for the comparison between G2 at 12% and 8% slope.

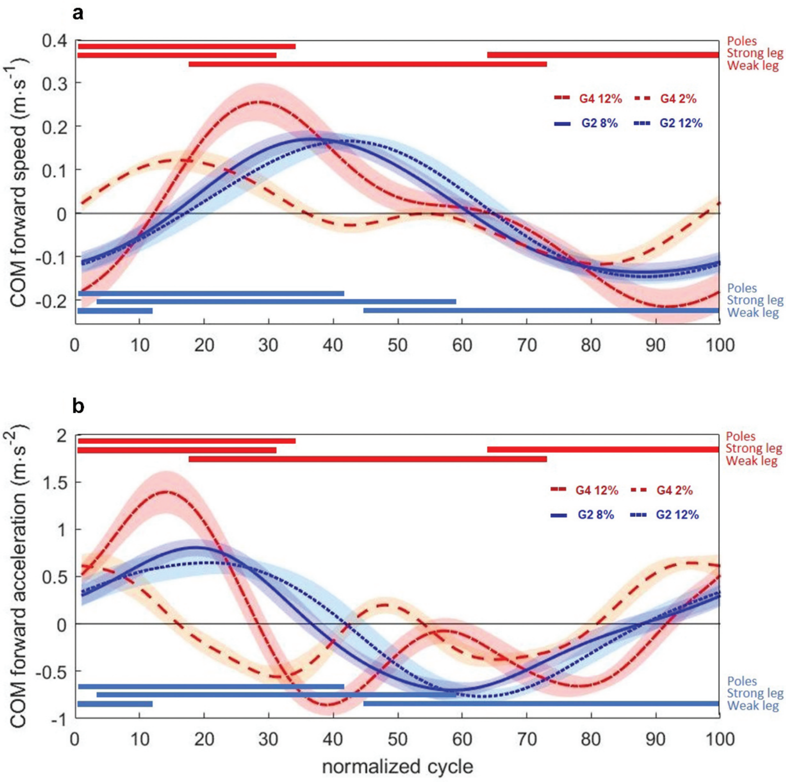

Figure 4. (a) Centre of mass (CoM) forward speed relative to the average cycle speed and (b) The CoM forward acceleration. Gear 4 (G4) at 8% slope is represented in dash-dot red lines, G4 at 2% slope in dashed red lines, gear 2 (G2) at 8% slope in solid blue lines, and G2 at 12% slope in dotted blue lines. Upper (red) and lower (blue) horizontal bars in represent the phases of contact for poles, strong side ski and weak side ski during the stride cycle for G4 and G2, respectively.

Discussion

The present study compares the temporal and kinematic patterns between the G2 and the G4 skating sub-techniques in cross-country skiing by analysing CoM motion with DTW and SPM methods. One main similarity between these two sub-techniques is that of one double poling movement on every second ski push. Based on that, Herzog et al. (2015) considered G2 and G4 to be the same unique sub-technique. However, in the present study, we find large differences in both forward, lateral and vertical movement of the CoM throughout the skiing cycle. Specifically, G4 is characterised by larger up and down movement, with two vertical acceleration peaks versus one smaller peak in G2. In addition, most spatio-temporal parameters showed clear differences between sub-techniques. All these findings were found both at equal slope-speed condition as well as at preferred slope-speed conditions for each sub-technique. Therefore, we deduce that G2 and G4 are two uniquely different sub-techniques, just like walking and running are different (Cavagna et al., Alexander).

The SPM analysis of G2 and G4 CoM forward acceleration reveals fundamental differences between the two sub-techniques: In G2, the upper body is more asymmetrical

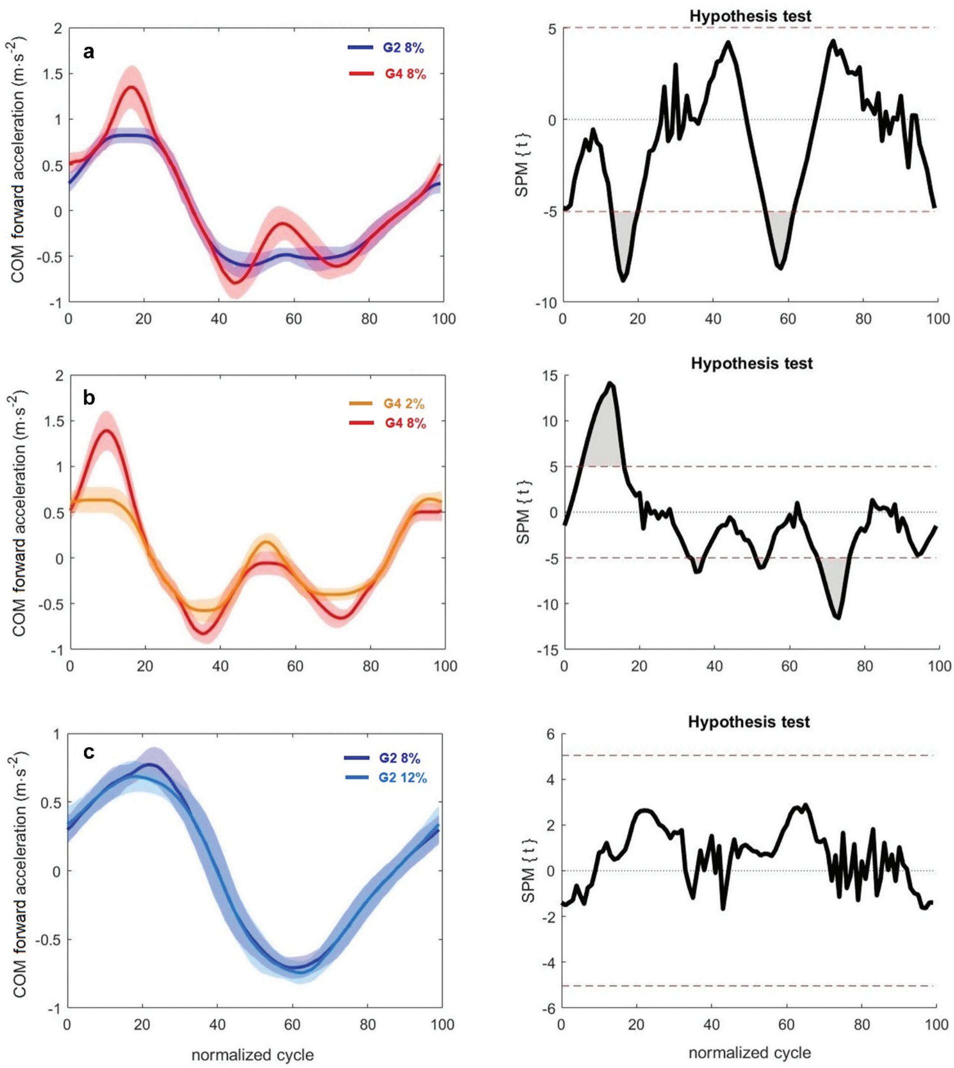

Figure 5. Dynamic time warping (DTW) applied to the centre of mass (CoM) forward acceleration relative to the average cycle speed, on the left-hand side, and the corresponding statistical parametric mapping (SPM) on the right and side. (a) Comparison of G4 in red and G2 in blue at 8% slope; (b) Comparison of G4 at 8% slope in red and G4 at 2% slope in orange; (c) Comparison of G2 at 8% slope in blue and G2 at 12% slope in light blue.

and shows higher shoulder rotation than in G4. On the strong side, the poles and ski start to push at the same time in G2, and the ski push on the weak side starts directly in order to come back quickly on the strong side. Accordingly, only one CoM forward acceleration phase is visible in the G2 cycle. In contrast, two forward acceleration phases are visible in the G4 cycle, where the highest peak occurs on the strong side when the poles and strong side ski push simultaneously. In G4, the smallest peak occurs on the weak side ski push which seem to involve a countermovement (leg flexion-extension, as shown previously in G4 (Hegge et al., 2014)), allowed by the longer time spent on the weak ski in

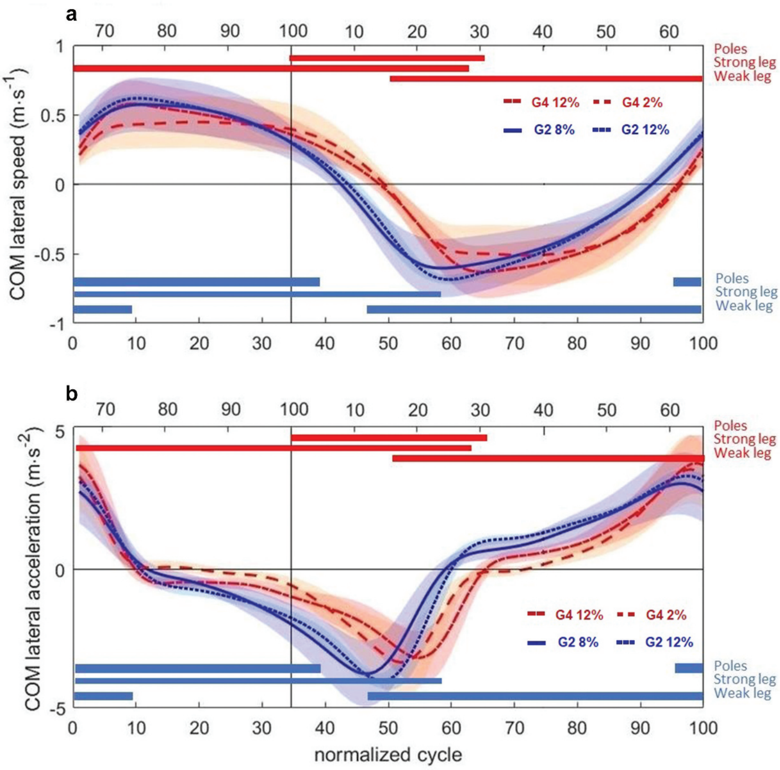

Figure 6. (a) Centre of mass (CoM) lateral speed and (b) The CoM lateral acceleration. Gear 4 (G4) at 8% slope is represented in dash-dot red lines, G4 at 2% slope in dashed red lines, gear 2 (G2) at 8% slope in solid blue lines, and G2 at 12% slope in dotted blue lines. Upper (red) and lower (blue) horizontal bars in represent the phases of contact for poles, strong side ski and weak side ski during the stride cycle for G4 and G2, respectively. The G4 cycle is shifted to match strong ski initial contact as cycle start.

G4. This is confirmed by the analysis at the preferred slope and speed condition for each sub-technique where this pattern is reinforced. At a steeper slope and slower speed, the G2 forward acceleration pattern also shows one phase, while at lower slope and faster speed, two distinct forward acceleration phases are found in G4. By using an accelerometer placed at the centre of the upper back, Marsland et al. (2012) obtained similar results, with a main and a secondary peak during the cycle in G4, and only one main deceleration phase in G2, even if two small acceleration peaks were observed. Myklebust et al. (2014) also used accelerometers placed on the hips to analyse G2 and G3 technique, and also found two peaks on G2 forward acceleration. This can be explained by the difference between the real COM behaviour analysed in our approach compared to the motion of a fixed body point by accelerometer sensors. Using three-dimensional reconstruction of the CoM, Gløersen et al. (2018) obtained similar motion for G4 as in our approach, on the three components. Moreover, the vertical component of the CoM motion also provides interesting insight, as vertical speed in G2 shows negative or close to zero values during the whole poling phase, while in G4, the poling phase start

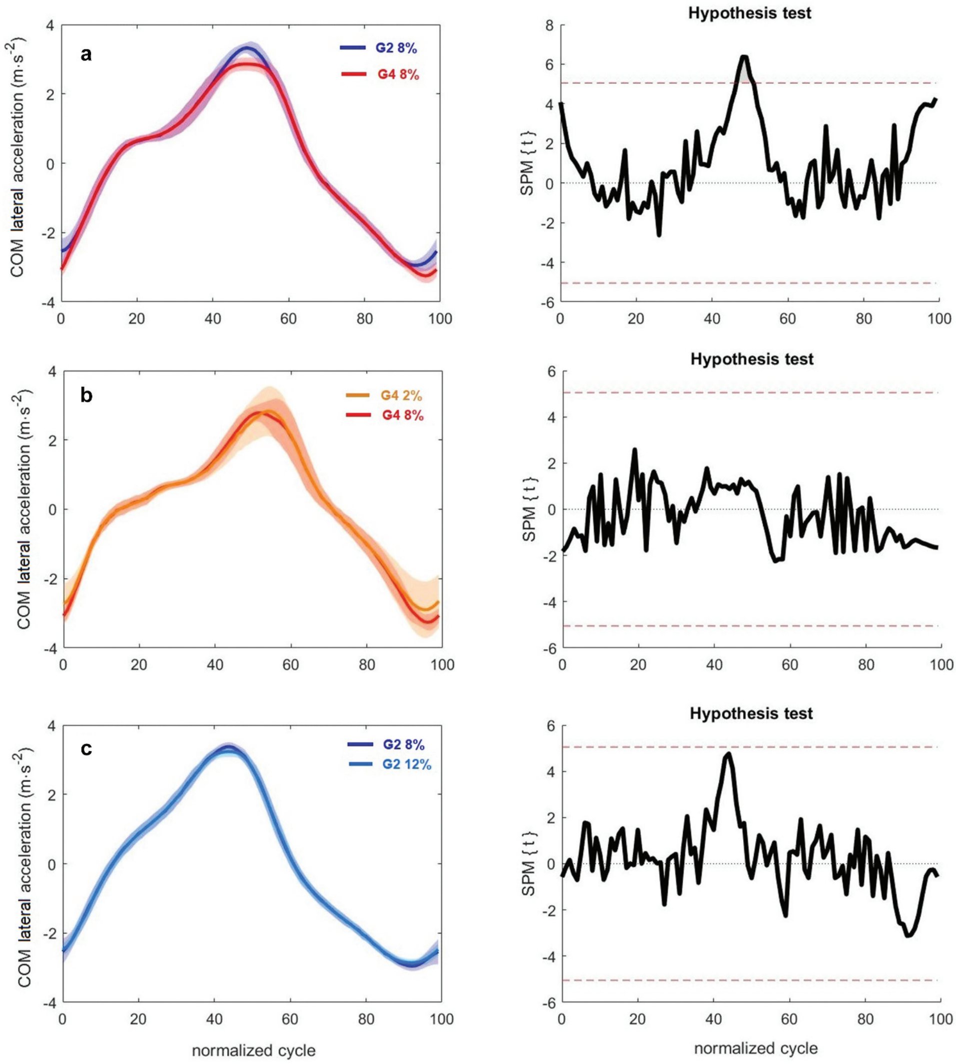

Figure 7. Dynamic time warping (DTW) applied to the centre of mass (CoM) lateral acceleration relative to the average cycle speed, on the left hand side, and the corresponding statistical parametric mapping (SPM) on the right and side. (a) Comparison of G4 in red and G2 in blue at 8% slope; (b) Comparison of G4 at 8% slope in red and G4 at 2% slope in orange; (c) Comparison of G2 at 8% slope in blue and G2 at 12% slope in light blue.

with negative vertical speed and finish with high positive vertical speed. Marsland et al. (2012) also obtained similar results, showing a different way of pushing on poles. It seems that G4 relies on a mechanism for pole propulsion similar to that in classic style double poling. Immediately preceding pole plant, the body is rapidly lowered (accelerating downwards, thus negative vertical speed), before it is actively heightened towards the end of poling time. As such, more body (mainly potential) energy (partly generated by leg work) may be used to increase pole force and power, as in DP (Danielsen et al., 2019). However, these leg motions and the related vertical movement of the CoM in G4 are also

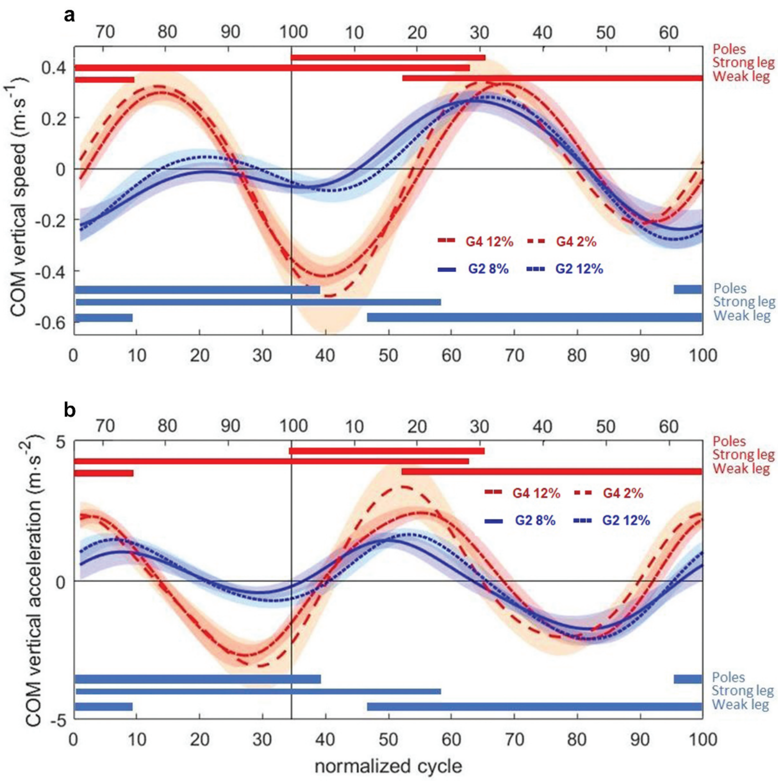

Figure 8. (a) Centre of mass (CoM) vertical speed and (b) The CoM vertical acceleration. Gear 4 (G4) at 8% slope is represented in dash-dot red lines, G4 at 2% slope in dashed red lines, gear 2 (G2) at 8% slope in solid blue lines, and G2 at 12% slope in dotted blue lines. Upper (red) and lower (blue) horizontal bars in represent the phases of contact for poles, strong ski and weak ski during the stride cycle for G4 and G2, respectively. The G4 cycle is shifted to match strong side ski initial contact as cycle start.

necessary to optimise the ski push-off (Hegge et al., 2014) independently of the poles. Furthermore, the lateral speed and acceleration of the CoM showed similar patterns across G2 and G4, once realigned based on legs cycles (by approximately one-third of a stride cycle).

Analysing parameters time normalised clearly indicates that temporal parameters linked to the legs (i.e., ski contact time, ski swing time and step time) are similar between G2 and G4 at the same slope and speed. Consequently, athletes spend the same relative amount of time in pushing on their skis. In contrast, relative poling time was longer in G2 than in G4, as observed by Nilsson et al. (2004). This means that the skiers spend less time to produce the required force in G4 compared to G2. This observation is also corroborated by the higher CoM amplitude on both vertical and lateral dimensions in G4, illustrating a more dynamic movement compared to G2. Therefore, a longer free glide phase was also obtained in G4, when the skier recovers from the dynamic acceleration during the push. This is also observed on the angle between skis, that is smaller in G4. Comparing the spatio-temporal cycle parameters of the two sub-techniques at their

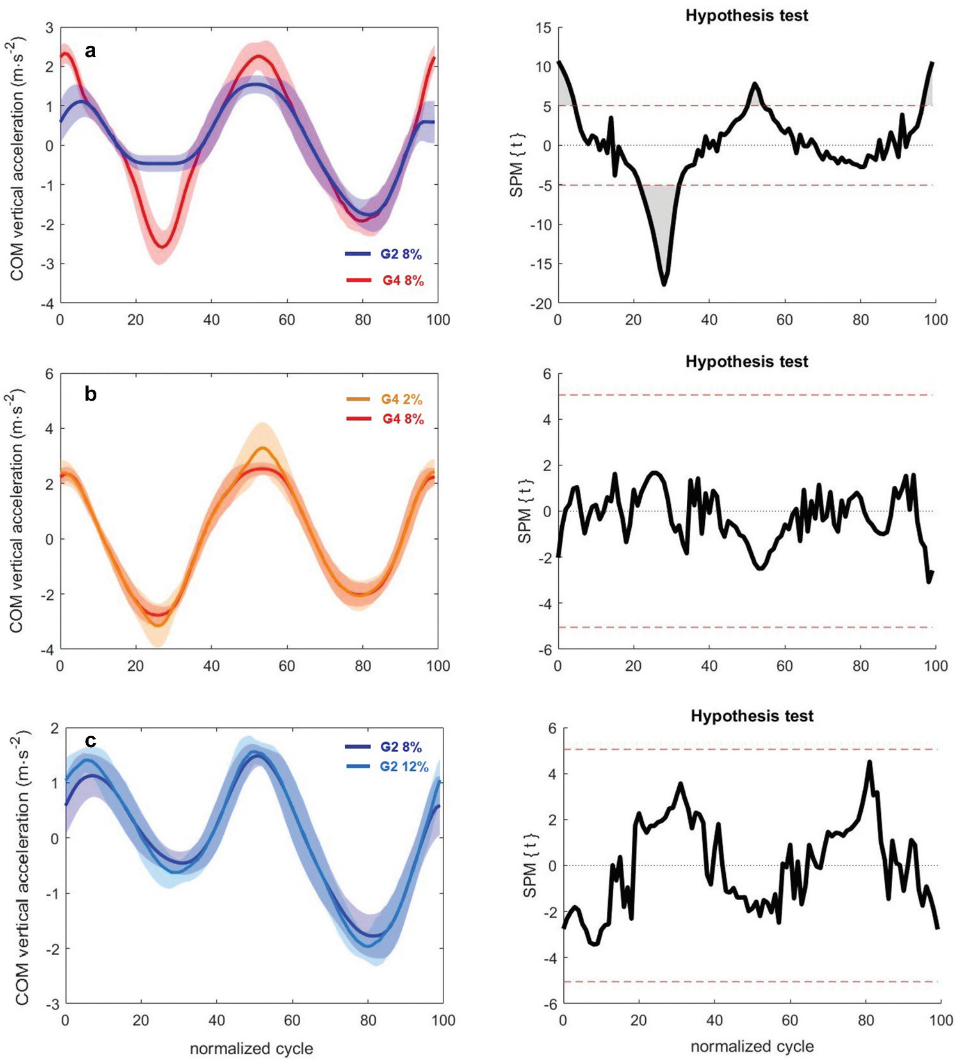

Figure 9. Dynamic time warping (DTW) applied to the centre of mass (CoM) vertical acceleration relative to the average cycle speed, on the left-hand side, and the corresponding statistical parametric mapping (SPM) on the right and side. (a) Comparison of G4 in red and G2 in blue at 8% slope; (b) Comparison of G4 at 8% slope in red and G4 at 2% slope in orange; (c) Comparison of G2 at 8% slope in blue and G2 at 12% slope in light blue.

preferred slope-speed condition, G4 at 2% slope and G2 at 12% slope reinforce this outcome since the free glide time is longer and the angle between skis is smaller for G4 at 2% and there is no free glide phase and a larger angle between skis at G2 at 12%. The pole and ski timing in G4 allow for a long free glide phase on each ski, adapted to high speed skiing and relatively flat slopes, while the timing on G2 allows for a more continuous generation of power, adapted to lower speed and steep slopes.

A deeper comparison of G2 and G4 performed at the same slope and speed shows that cycle times are longer in G4, which is mainly due to the longer ski contact time on the strong side in G4 and a shorter ski swing time on the weak side in G2. This observation is reinforced when looking at temporal parameters related to poles, as a shorter poling time and a longer pole swing time is visible in G4. This allows a small period of free glide during weak side in G4, which is even more visible on a less inclined slope. G4 shows a motion pattern with higher amplitudes, and with skis orientated more in the forward direction. Moreover, the CoM forward acceleration in G4 showed higher peaks, resulting in higher CoM forward speed amplitude compared to G2. Williams and Cavanagh (1987) observed a better running economy on athletes who were able to reduce the variation of speed during the stride cycle. This was explained by lower energy cost needed to produce acceleration of the body.

Poling time, pole swing time and angle between skis and ski push time were different for the two sub-techniques on the same slope-speed condition (G2 vs G4 8% 10 km·h^{-1}) and for the different slope-speeds combinations in G2 (8% 10 km·h^{-1}vs 12% 7 km·h^{-1}) and G4 (8% 10 km·h^{-1} vs 2% 21 km·h^{-1}). As these parameters differ both between sub-techniques and between speed/slope for a given sub-technique, it can be speculated that these parameters are main drivers with respect to preferred choice of sub-technique between G2 and G4 for a given slope and speed (Sollie et al., 2021). Nevertheless, as athletes normally use G3 between G2 and G4, the 8% slope and 10 km·h^{-1} speed may be more appropriate for the G3 sub-technique. This condition was not tested in the present study, but Sandbakk et al. (2012) provided spatio-temporal analysis of the G3 sub-technique on a 8% slope. Ski contact and swing time in G3 were more comparable to G4 than G2, while poling time and relative pole swing time were more comparable in G3 and G2, but a lower percentage of poling time for G4. A parallel can be drawn with cycling (Chavarren & Calbet, 1999) or running (Cavagna et al., 1997), where an optimal pedalling and stride frequency, respectively, allows the best efficiency. One may, therefore, speculate that poling times and/or pole propulsion related mechanisms are the predominant factor affecting the choice of sub-technique between G4 and G3. Once reaching higher slope or lower speed, a new strategy (i.e., G2) is performed, with one single progressive acceleration pattern during the stride.

Several methodological considerations should be clarified; First, conducting the experiment on roller skis limits the interpretation for on-snow skating conditions. Although the main mechanisms underlying our conclusions seem rational, inclusion of only male elite athletes as participants also limits the generalisation to women or skiers on a lower level. Nevertheless, having elite athletes performing G2 and G4 in a specific situation where they would not usually use these sub-techniques was chosen as the best solution to obtain consistent results. However, although we found no differences between the use of sub-techniques when comparing outcomes between their preferred utilisation range and the common condition at 8%, there is still a possibility that this similar slope and speed condition induced unnatural movements for some of the athletes. Another element that could affect the results is the fatigue accumulated during the two-day protocol. We believe that the randomisation of the conditions, the fact that the analysed conditions were submaximal and that the participants were elite athletes used to long training session twice daily reduce the possibility having an undesired effect of fatigue.

Conclusion

This study illustrates the clear differences in movement patterns between the G2 and G4 sub-techniques in roller ski skating, validating the hypothesis of two different sub-techniques. The major difference was that one forward acceleration phase is visible in G2 while two phases are present in G4. The more continuous propulsion in G2 allows for maintaining a more constant speed on steep slopes and low speeds when this sub-technique is preferred. In contrast, the achievement of high speeds while skiing on flatter terrain seems to require more dynamic motion with shorter, more explosive propulsion periods allowed for in G4. This clearly illustrates why G2 and G4 should be denoted as two different sub-techniques.

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ORCID

F. Meyer http://orcid.org/0000-0002-1434-6542

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