The interval-based physiological and mechanical demands of cross-country ski training

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Abstract

Purpose: To investigate fluctuations in speed, work rate and heart rate (HR) when cross-country (XC) ski skating across varying terrain at different endurance training intensities. ***Methods:*** Seven male Norwegian junior skiers performed maximal speed (V_{max}) tests in both flat and uphill terrain. Thereafter, 5-km sessions at low- (LIT), moderate- (MIT), and high-intensity (HIT) were performed based on their own perception of intensity, while monitored by a global navigation satellite system (GNSS) with integrated barometry and accompanying HR monitor. ***Results:*** Speed, HR and rating of perceived exertion gradually increased from LIT to MIT and HIT, both for the total course and in flat and uphill terrains (all $P < .05$). Uphill work rates (214 [24] W, 298 [27] W and 350 [54] W for LIT, MIT and HIT) and the corresponding % of maximal HR (79.2 [6.1]%, 88.3 [2.4]% and 91.0 [1.7]%) were higher compared to flat terrain (159 [16] W, 206 [19] W and 233 [72] W versus 72.3 [6.3]%, 83.2 [2.3]% and 87.4 [2.0]% for LIT, MIT and HIT) (all $P < .01$). In general, ~13%-point lower utilization of maximal work rate (WR_{max}) was reached uphill compared to flat terrain at all intensities (all $P < .01$). ***Conclusions:*** XC ski training across varying terrain is clearly interval-based, both in terms of speed, external work rate and metabolic intensity for all endurance training intensities. Although work rate and HR were highest in uphill terrain at all intensities, the utilization of WR_{max} was higher in flat terrain. This demonstrates the large potential for generating external work rate when uphill skiing, and the corresponding down-regulation of effort due to the metabolic limitations.

Keywords: endurance training, global navigation satellite system, high-intensity training, skating style, XC skiing

Introduction

Cross-country (XC) skiing is regarded as one of the most demanding endurance sports and involves whole body exercise of varying techniques through racing times ranging from a few minutes to several hours. The competition terrain fluctuates between uphill, flat and downhill sections, in which the greatest performance variation is seen in the uphill terrain,[1-4] and the relative time spent on uphill, flat and downhill sections contribute in that order to overall time-trial performance.[5]

Due to the varying terrain in XC skiing, the competitions are interval-based with increased generation of external work rate and metabolic intensity uphill, and reduced effort in the downhill terrain.[1,4-16] Currently, these factors have only been examined in a performance setting at high-intensity (HIT), and no previous study has investigated whether the same occurs while training at low- (LIT) and moderate-intensity (MIT) that reflects around 80% of a XC skier's overall training.[17-25]

Heart rate (HR) is commonly normalized to its maximal value (HR_{max}) to reflect an individual's internal metabolic intensity/effort during training and competition.[1,4,9,13,15,16] However, the corresponding utilization of the maximal external work rate (WR_{max}) has not yet been addressed in XC skiing, which is more complex since WR_{max} varies with the changes in external condition. Such information would go beyond previous analyses of speed profiles[1,4,5] that is highly influenced by the variations in opposing forces from snow-ski friction, air drag and gravity across different terrains. In contrast, work rate and the fractional utilization of WR_{max} provide a more universal understanding on how skiers distribute power during training and competition. Concurrent information on external work rate and HR fluctuations across the varying terrain while skiing would therefore be imperative for optimizing training programmes and evaluating the actual load for XC skiers, biathletes and Nordic combined skiers.

In this context, a few recent studies have examined the proportion of maximal speed (V_{max}) utilized in different terrains. Here, both Andersson et al.[1] and Haugnes et al.[26] reported that skiers reach ~80-85% of their maximal speed (V_{max}) on flat terrain in the finish sprint during a simulated skating sprint time trial on snow. In the classical style, similar values were found for HIT both in flat and uphill terrain, whereas a higher proportion of V_{max} was utilized on flat compared to uphill terrain during LIT (~65 versus ~54%), even though the relative HR was highest uphill (~65 versus ~75%).[27] Whether work rate would follow the same pattern and if these previous findings would apply for skating with LIT and MIT currently remains unknown.

Therefore, the present study was designed to investigate the fluctuations in speed, work rate and HR when XC ski skating across varying terrain, from low- to high-intensity endurance training. This experiment was performed on snow with intensity-prescriptions based on the skiers' own perception of intensity, in which we hypothesized that both work rate and HR would be clearly interval-based with highest values achieved in uphill terrain for all intensities.

Methods

Participants

Seven elite male junior Norwegian XC skiers volunteered to participate in the study. Their anthropometric and physiological characteristics are shown in Table 1. This study was approved by the Norwegian Centre for Research Data (NSD), and participants were fully informed of its nature before providing their written consent to participate.

Table 1

Design

Initially, all skiers were tested for peak oxygen uptake (VO_2peak) during treadmill roller ski skating in the laboratory. Thereafter, on a separate day, the skiers' V_{max} were tested in both flat and uphill terrain. This was followed by three 5-km sessions in varying terrain, where they were instructed to perform LIT, MIT and HIT based on their own perception of intensity according to the target RPE values provided. The skiers were investigated with respect to speed and HR using a global navigation satellite system (GNSS) device with integrated barometry and accompanying HR monitor. The work rate was estimated from the combined contribution of work against gravity, gliding friction and air resistance. The snow friction and weather conditions were stable throughout the whole test day with light wind, partly cloudy, air temperature of -18°C, snow temperature of -19°C, ~55% humidity and atmospheric pressure of ~1008.3 hPa. The course was covered with hard packed mixed snow and was machine prepared in the morning prior to testing.

Methodology

A VO_2peak test on roller-ski employing the G3-skating technique was performed on a 5×3-m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands), with standardized procedures published previously,[6] while employing open-circuit, indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Rating of perceived exertion (RPE) was recorded using the 6 to 20 point Borg Scale.[28]

Prior to testing, the skiers warmed-up according to their own individual program and were instructed to prepare and use their own ski equipment for the prevailing conditions including grinds, structure and waxing. The skiers performed two 20-m V_{max} tests, each separated with 3-minute of light activity, both in a flat section (S8) and an uphill section (S2) using the skating techniques G3 and G2, respectively (Figure 1). The skiers performed a self-selected run-up and were instructed to reach the highest possible speed when entering the V_{max} sections. V_{max} was calculated based on time from two sets of photocells with 1000 Hz resolution (TC-Timer; Brower Timing Systems, Draper, UT, USA) placed at start and finish of the V_{max} sections, 20 cm above the ground and with 250 cm transmitter-reflector spacing. A 10-minute recovery period followed the V_{max} tests before each skier where instructed to perform three 5-km sessions with training intensity corresponding to RPE-values for LIT (RPE 11), MIT (RPE 15) and HIT (RPE 18), respectively, with 3-minute of light activity in between. RPE was assessed immediately after the three 5-km sessions overall for the total course and for the separate terrains (uphill, flat and downhill). Each 5-km had 1-minute interval start where drafting was prohibited to avoid the potential of skiers saving time and energy by reduced drag.

Course and elevation profiles were determined with a Garmin Forerunner 920XT (Garmin Ltd., Olathe, KS, USA, abbreviated as Gar-920XT) wrist watch, with both a GNSS and a built-in barometrical altimeter, and was used to define a reference course according to Sandbakk et al.[5] During the three 5-km sessions, each skier wore the same Gar-920XT that collected position and HR data at a sampling rate of 1 Hz. Further, we ensured proper GPS fixing and minimized inaccuracy, as previously described by Sandbakk et al.[5] The total distance was 5140 m (3x1713 m) with varied topography based on a course profile divided into uphill, flat and downhill that made up 30, 29 and 41% of the course, respectively. Each lap was divided into 8 different sections (S1-S8), according to terrain topography (see Figure 1). One lap consisted of two uphill sections (S2, S6) with mean inclines of ~13% and ~9% and section length of 212 m and 302 m, four flat sections (S1, S3, S5, S8) with section length of 25 m, 78 m, 181 m and 203 m, and two downhill sections (S4, S7) with mean slopes of approximately -8% and -10% and section length of 414 m and 298 m. The maximal difference in elevation was 29 m with a total climb of 55 m per lap. The time each skier spent in a section was calculated based on virtual split times. Section speed was calculated by dividing the length of a section by the section time of the skiers. The Gar-920XT has recently been validated,[29] with a reported section time error between 0.4 and 0.9 second for 20 to 180-m long sections, and with error in section time plateauing for longer sections. This shows that the accuracy in section time and section speed should be sufficient for answering the aim of this study.

Figure 1

The coefficient of snow friction (μ_s) was measured 30 minute prior to the start of the V_{max} tests and immediately after the end of the 5-km tests according to Sandbakk et al.[6] The skier glided passively down a ~5% downhill slope onto a 20-m flat zone, sitting in a tucked down position with an initial speed of ~3 $m \cdot s^{-1}$. The loss of speed was used to calculate the deceleration and subsequently, the friction coefficient ($\mu_s = a \cdot g^{-1} = .026$), ignoring the force of air drag which was minimal at this slow speed. The wind drag coefficient ($A \cdot C_d$) incorporated in this study, has previously been estimated as .35 m^2 from wind tunnel testing by Sandbakk et al.[6]

The work rate was calculated for the V_{max} sections during the V_{max} tests and the three 5-km in the final lap according to Sandbakk et al.[6] as the sum of power (P_{tot}) against gravity (P_g), friction (P_f), and air drag (P_d), with V being the average speed in the terrain sections, $\propto$ the angle of incline, μ_s the coefficient of friction, ρ the density of the air according to air temperature (1.37 g/cm^3), A the exposed frontal area of the skier, and C_d the drag coefficient (Eq. II).

$$Ptot = P_g + P_f + P_d \quad \text{(IIa)}$$
$$Ptot = m \cdot g \cdot \sin(\propto) \cdot v + m \cdot g \cdot cos(\propto) \cdot \mu_s \cdot v + 0.5 \cdot \rho \cdot v^3 \cdot A \cdot C_d \quad \text{(IIb)}$$

Statistical Analysis

Shapiro–Wilks test and comparison of histograms were used to assess the normality of the distribution of the variables, and all data are presented as mean (SD). A two-way repeated measures ANOVA were used for analysing the effect of intensity (LIT, MIT, HIT) x terrain (uphill, flat, downhill) on HR, RPE, speed, and work rate. Post hoc comparisons were made using a Bonferroni correction. In cases where Mauchly's test of sphericity indicated that the assumption of sphericity was violated, a Greenhouse-Geisser correction was performed. The Gar-920XT failed to register HR and caused missing data in one case (n=1). The statistical significance level was set at $\alpha < .05$, and all statistical analyses were processed using SPSS 24 Software for Windows (SPSS Inc., Chicago, IL, USA) and Office Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

Results

As expected, higher intensity resulted in increased average speed for the total course and in all terrains (P < .01; Figure 2 and Table 2), except from MIT to HIT in downhill terrain. The difference in average speed for the total course was higher for MIT versus LIT (1.2 [0.3] $m \cdot s^{-1}$) compared to HIT versus MIT (0.5 [0.1] $m \cdot s^{-1}$) (all P < .002; Figure 2). Furthermore, the relative time in flat terrain did not differ between the intensities, whereas the skiers spent relatively less time uphill and relatively more time downhill with increased intensity (all P < .05; Table 2). A significant interaction effect between intensity and terrain on speed was found (P < .001; Table 2) with post-hoc analyses presented in Table 2.

Figure 2

The skier's V_{max} and WR_{max} were on average 8.8 (0.4) $m \cdot s^{-1}$ and 326 (26) W in flat terrain and 4.9 (0.3) $m \cdot s^{-1}$ and 595 (62) W in uphill terrain, respectively. The work rate was higher in uphill section (S2) as compared to flat section (S8) at all intensities, and increased with intensity (all P < .05; Table 3), except from MIT to HIT in flat terrain. The percentage of their V_{max} and WR_{max} was lower in the uphill compared to flat terrain at all intensities (all P < .01; Table 3), except for $\%WR_{max}$ during HIT. No significant interaction effect between intensity and terrain on work rate was found. The average work against gravity, friction, and air resistance for all intensities was estimated to be approximately .0, 63.7, and 36.3% on the flat section (S8) and 82.9, 15.8, and 1.3% on the uphill section (S2), respectively, of the total work rate. As expected, the relative contribution from work rate against air drag increased slightly with higher speed in the uphill terrain, and logically follows the pattern found in previous research.[6,9]

The skier's average HR for the total course and in all terrains increased with intensity (all P < .05; Figure 3 and Table 2). The difference in average HR for the total course was higher for MIT versus LIT (10.3 [4.8] $\%HR_{peak}$) compared to HIT versus MIT (3.3 [1.6] $\%HR_{peak}$) (all P < .004; Figure 3). A significant interaction effect between intensity and terrain on HR was found (P < .001; Table 2), with post-hoc analyses presented in Table 2. Correspondingly, RPE was higher with increased intensity for the total course (P < .01; Table 2), and a significant main effect of terrain on RPE was found, with higher RPE for uphill compared to flat and downhill, as well as for flat compared to downhill (P < .01; Table 2). No significant interaction effect between intensity and terrain on RPE was found.

Table 2

Table 3

Figure 3

Discussion

The main finding of the present study was that XC ski training across varying terrain is clearly interval-based, both in terms of speed, external work rate and metabolic intensity (indicated by HR) for all endurance training intensities. Both the maximal potential to generate external work rate (WR_{max}), as well as work rate and HR (as a proxy for metabolic intensity) during LIT, MIT and HIT were highest in uphill terrain. However, the proportion of V_{max} and WR_{max} utilized during uphill endurance training decreased compared to the corresponding values achieved in flat terrain.

The current results provide novel insights into endurance training in XC skiing. Although the skier's relative time spent in different sections of terrain during training in general is comparable with time distributions reported in distance and sprint races,[1,4,5] relatively less time was spent uphill and relatively more time was spent downhill with increased intensity. Therefore, the speed fluctuation across the terrains was greater during LIT compared to MIT and HIT. This means that the uphill skiing speed during LIT was relatively low in order to keep a relevant metabolic intensity, whereas the corresponding skiing speed downhill is high and does not differ much from MIT and HIT. Thus, downhill terrain sections give skiers the opportunity to train with competition-specific speed and techniques at relatively low metabolic load. Such information is of high relevance to take into account when evaluating and planning the large amount of LIT and MIT performed by XC skiers.

The reduced uphill speed is further exemplified by the lower percentage of V_{max} used uphill compared to on flat terrain with LIT compared to HIT, although all skiers used lower $\%V_{max}$ uphill compared to the flat terrain at all intensities. This is also previously shown for skiers using the classical style during 5-km sessions with LIT and HIT.[27] Overall, the practical implications of this might be that skiers should be advised to use many hours relatively close to their competition speed in flat and downhill terrains with LIT, thereby using training during this type of terrain to induce large technical improvements. In contrast, skiers need to reduce speed much below their competition speed when climbing uphill during LIT. Therefore, the uphill speed is relatively low with LIT, which means that prioritizing HIT sessions in uphill terrain may be required for training with a competition-relevant speed and technique. These differences in speed between uphill and flat training in XC skiing are further exemplified by ~52% of the skier's V_{max} being used uphill during MIT, although their relative HR was ~88% of HR_{peak}. In contrast, the utilization of $\%V_{max}$ for flat terrain during MIT was ~78% at a lower percentage of HR_{peak} than used uphill. However, the skiers in this study were tested in a course with competition-specific terrain, which might not be the preferred one for all types of sessions. In this context, our data shows that coaches and athletes should carefully consider the choice of training terrain, depending of the goal of a given training session.

Many previous studies have shown that higher work rates are obtained on uphill terrain in XC skiing during actual and simulated competitions.[4,6-12,14,16] However, this study provides additional information about XC skiers' ability to generate WR_{max} in flat and uphill skating on snow, and the percentage of WR_{max} achieved in both terrains during LIT, MIT and HIT. Specifically, the skiers reached ~595 W (7.75 $W \cdot kg^{-1}$) with the G2-skating technique on uphill terrain, which is 80% greater than the ~326 W (4.23 $W \cdot kg^{-1}$) performed with the G3-skating technique on the flat. The corresponding absolute work rates for flat and uphill terrains were ~159 versus ~214 W during LIT, ~206 versus ~298 W during MIT and ~233 versus ~350 W during HIT. However, a different pattern was found when these values are expressed relative to WR_{max}, with ~49 versus ~36 %WR_{max} for LIT, ~63 versus ~50 %WR_{max} for MIT and ~72 versus ~59 %WR_{max} for HIT in uphill and flat terrain, respectively. Altogether, these results demonstrate higher work rates and lower percentage of WR_{max} in the uphills compared to flat terrain and thereby provide new information about how skiers pace across changing terrain. More specifically, the larger potential to generate WR_{max} in uphill requires skiers to choose a lower fractional utilization of WR_{max} to keep the metabolic cost on a sustainable level.

The high potential for generating high uphill work rates also contributes to explain the higher HR (as a proxy for metabolic intensity) found in uphill compared to flat terrain, although the average HR for all intensities for the total course was in accordance with earlier described intensity zones.[25] In general, we found that the skiers chose the same pacing pattern during LIT and MIT as previously found in actual competitions, with higher intensity uphill and lower intensity on flat and downhill terrain. However, in line with the greater speed differences during LIT, also HR fluctuated more during LIT compared to MIT and HIT. This highlights that skiers in their daily training perform natural interval-training, where intensity is dependent on the terrain, which might be most pronounced during LIT. Still, HR does not fully reflect the metabolic work and the higher HR seen in the downhill compared to the flat terrain is likely a result of delayed HR kinetics when the skiers enter the downhill terrain directly after skiing uphill. This has previously been reported by Bolger et al.[4] in world-class skiers during distance races across varying terrain, and although this effect is clearly greater at high intensities, we here show that it is present during all the endurance training intensities. The greater effect of the delayed HR response during HIT is due to the fact that work rates exerted in the uphill terrain drives the intensity above maximal oxygen uptake[6,9,11] and causes oxygen deficit, which eventually leads to an additionally increase in HR in the subsequent terrain. This gives less opportunity for recovery, resulting in a relatively higher and more stable HR throughout the course during HIT. In contrast, more fluctuating intensity is seen during LIT. Overall, these results are important to be aware of when prescribing and analysing training intensity during XC skiing training.

Practical Applications

Since XC skiers are able to train relatively close to their competition speed during LIT and MIT in flat and downhill terrain, this indicates a potential for inducing technical improvements over large volumes of training at these intensities. On uphill terrain, the maximal potential to generate external power is larger than on flat and downhill sections, which can induce great benefits during anaerobic training. However, for endurance training, especially with LIT and MIT, the proportion of V_{max}/WR_{max} utilized in uphill terrain needs to be down-regulated due to the more limited potential of the metabolic system to sustain the work. Therefore, the uphill speed is relatively low with LIT and MIT, which means that prioritizing many of the HIT sessions in uphill terrain may be required for training with a competition-relevant speed and technique. Overall, the integrated understanding of how speed, work rate and HR fluctuates across varying terrains are important for coaches and athletes to be aware of both when planning and analysing XC skiing training in different types of terrain and across intensities.

Conclusions

XC ski training across varying terrain is clearly interval-based, both in terms of speed, external work rate and metabolic intensity for all endurance training intensities. This is unique compared to most other modes of exercise where most of the training is performed at steady state intensities over long time-spans. Although work rate and HR were highest in uphill terrain at all intensities, the utilization of V_{max} and WR_{max} decreased compared to the corresponding values achieved in flat terrain. This demonstrates the large potential for generating external work rate when uphill skiing, and a corresponding down-regulation of effort due to the more limited potential of the metabolic system to sustain the work rate over time.

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Table 1. Anthropometric and physiological characteristics of 7 elite male junior cross-country skiers involved in this study (Mean [SD]).

Variable	
Age (y)	18.3 (0.5)
Body height (cm)	180 (6)
Body mass (kg)	76.9 (6.5)
Body mass index ($kg \cdot m^{-2}$)	23.7 (2.3)
Peak heart rate ($beats \cdot min^{-1}$)	198 (10)
VO_2peak ($L \cdot min^{-1}$)	5.17 (0.64)
VO_2peak ($mL \cdot min^{-1} \cdot kg^{-1}$)	67.2 (5.7)

VO_2peak Peak aerobic capacity.

Table 2. Skiing time, speed, heart rate, as well as rating of perceived exertion (RPE) over the total course and different terrains while 5-km cross-country skiing with the skating style at low- (LIT), moderate- (MIT) and high-intensity training (HIT) for 7 elite male junior cross-country skiers (Mean [SD]).

Variable	LIT	MIT	HIT
Total course			
Time (s)	1238 (34)	961 (52)**	874 (48)$^{\#\#}$
Speed ($m \cdot s^{-1}$)	4.1 (0.1)	5.3 (0.3)**	5.9 (0.3)$^{\#\#}$
Heart rate (%peak)	76.3 (6.2)	86.6 (2.2)**	89.8 (1.8)$^{\#}$
RPE (Borg 6-20)	9.6 (1.9)	14.0 (0.8)**	17.9 (1.1)$^{\#\#}$
Uphill terrain			
Time (%)	56.9 (0.9)^{c,f}	53.7 (0.8)^{**,c,f}	51.6 (1.5)$^{\#,c,f}$
Speed ($m \cdot s^{-1}$)	2.2 (0.1)^{c,f}	3.0 (0.2)^{**c,f}	3.4 (0.3)$^{\#\#,c,f}$
Heart rate (%peak)	79.2 (6.1)^{c,e}	88.3 (2.4)^{**,c}	91.0 (1.7)$^{\#,b}$
RPE (Borg 6-20)	11.3 (2.0)^{b,e}	15.4 (0.5)^{**,c,f}	18.3 (1.3)$^{\#\#,b,f}$
Flat terrain			
Time (%)	22.3 (0.6)^{c,i}	22.8 (0.5)^{c}	23.1 (0.5)^{c,h}
Speed ($m \cdot s^{-1}$)	4.9 (0.1)^{c,i}	6.2 (0.4)^{**,c,i}	6.8 (0.4)$^{\#\#,c,i}$
Heart rate (%peak)	72.3 (6.3)^{c,g}	83.2 (2.3)^{**,c,i}	87.4 (2.0)$^{\#\#,b,i}$
RPE (Borg 6-20)	7.3 (1.0)^{b,g}	12.1 (1.1)^{**,c,h}	15.6 (1.6)$^{\#\#,b,h}$
Downhill terrain			
Time (%)	20.5 (0.5)^{f,i}	23.2 (0.7)^{**,f}	25.0 (1.3)$^{\#\#,f,h}$
Speed ($m \cdot s^{-1}$)	8.4 (0.2)^{f,i}	9.6 (0.3)^{**,f,i}	9.8 (0.2)^{f,i}
Heart rate (%peak)	73.6 (6.7)^{e,g}	86.4 (2.2)^{**,i}	90.3 (2.1)$^{\#\#,i}$
RPE (Borg 6-20)	6.3 (0.5)^{e,g}	9.7 (1.9)^{**,f,h}	12.9 (2.1)$^{\#\#,f,h}$

All variables (N=7), except for heart rate (N=6).
Significantly different from the corresponding value for LIT at the same terrain, $^{*}P$ <0.05; $^{**}P$ <0.01; $^{***}P$ <0.001.
Significantly different from the corresponding value for MIT at the same terrain, $^{\#}P$ <0.05; $^{\#\#}P$ <0.01; $^{\#\#\#}P$ <0.001.
Significant difference for the corresponding value between uphill and flat at the same intensity, ^{a}P <0.05; ^{b}P <0.01; ^{c}P <0.001.
Significant difference for the corresponding value between uphill and downhill at the same intensity, ^{d}P <0.05; ^{e}P <0.01; ^{f}P <0.001.
Significant difference for the corresponding value between flat and downhill at the same intensity, ^{g}P <0.05; ^{h}P <0.01; ^{i}P <0.001.

Table 3. Speed and work rate (in absolute values and % of the maximal speed/work rate achieved in the same section) for a representative uphill (S2) and flat (S8) section during 5-km cross-country skiing with the skating style at low- (LIT), moderate- (MIT) and high-intensity training (HIT) for 7 elite male junior cross-country skiers (Mean [SD]).

Variable	LIT	MIT	HIT
Uphill terrain			
Speed ($m \cdot s^{-1}$)	1.8 (0.1)^{c}	2.5 (0.2)^{**,c}	3.0 (0.3)$^{\#\#,c}$
% of maximal speed	37.5 (3.4)^{c}	52.0 (3.9)^{**,c}	60.4 (4.6)$^{\#\#,b}$
Work rate (W)	214 (24)^{c}	298 (27)^{**,c}	350 (54)$^{\#,b}$
% of maximal work rate	36.0 (3.5)^{b}	50.2 (3.8)^{**,b}	58.5 (4.6)$^{\#\#}$
Flat terrain			
Speed ($m \cdot s^{-1}$)	5.9 (0.2)^{c}	6.9 (0.5)^{*,c}	7.3 (1.2)^{c}
% of maximal speed	67.2 (4.5)^{c}	78.2 (4.7)^{*,c}	83.0 (14.9)^{b}
Work rate (W)	159 (16)^{c}	206 (19)^{*,c}	233 (72)^{b}
% of maximal work rate	49.0 (6.4)^{b}	63.4 (6.2)^{*,b}	72.2 (23.8)

All variables (*N*=7).
Significantly different from the corresponding value for LIT at the same terrain, $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$.
Significantly different from the corresponding value for MIT at the same terrain, $^{\#}P<0.05$; $^{\#\#}P<0.01$; $^{\#\#\#}P<0.001$.
Significant difference for the corresponding value between uphill and flat at the same intensity, $^{a}P<0.05$; $^{b}P<0.01$; $^{c}P<0.001$.

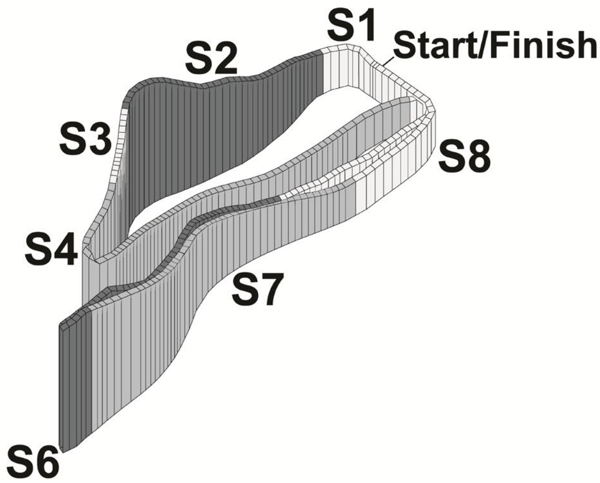

Figure 1 – Three-dimensional illustration of the 8 sections (S1-S8) of the 1.7-km course examined in the current study.

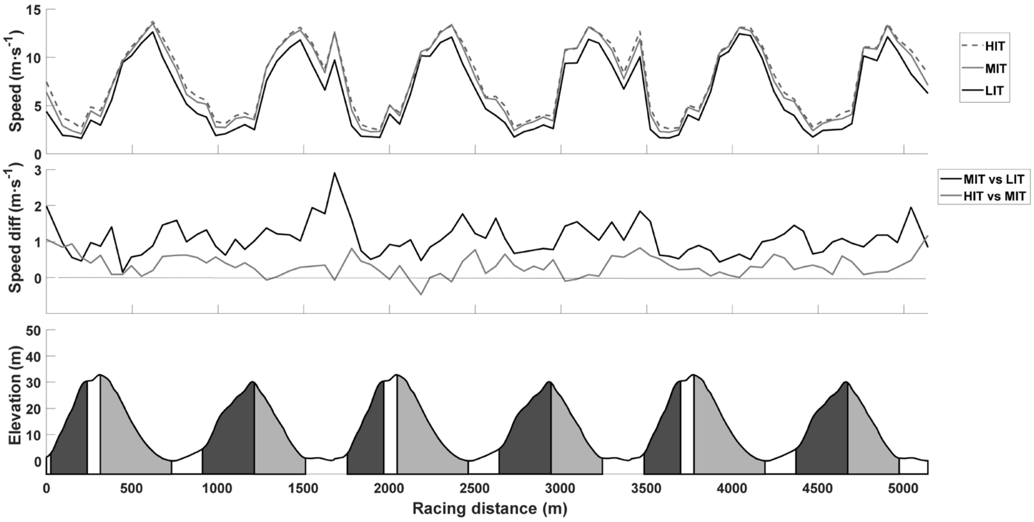

Figure 2 Skiing speed and speed differences between low- (LIT), moderate- (MIT) and high-intensity training (HIT) while skiing 5-km with the skating style among 7 elite male junior cross-country skiers.

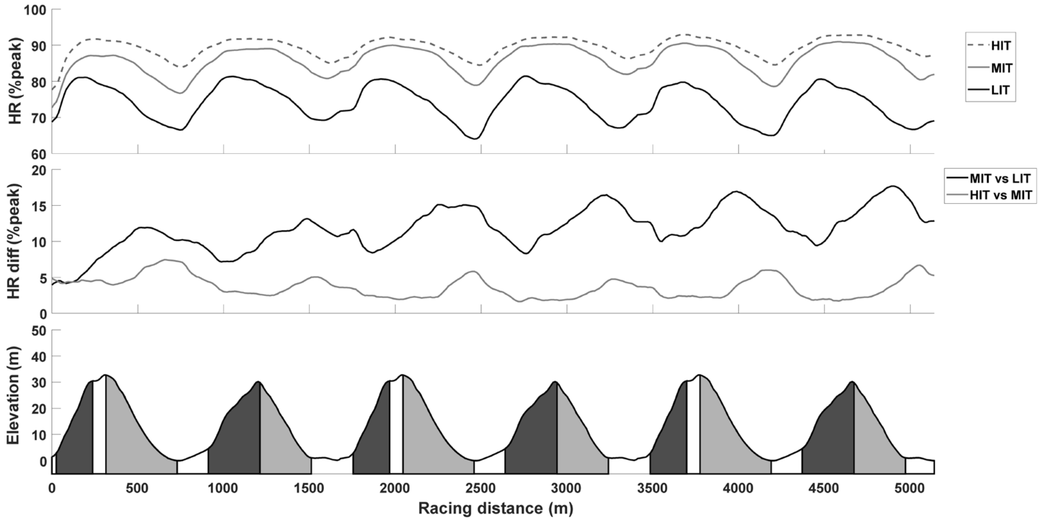

Figure 3 Heart rate (HR) in percentage of peak HR and the difference in HR between low- (LIT), moderate- (MIT) and high-intensity training (HIT) while skiing 5-km with the skating style among 6 elite male junior cross-country skiers.