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The effect of exercise intensity on speed and heart rate profiles, work rate and kinematics in skating cross-country skiing

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Abstract

The exercise intensity during cross-country skiing competitions fluctuates. However, it is presently not known to what extent this occurs during ski-specific training at the different intensities. The aim of the present study was to investigate the actual speed and heart rate profiles, work rate, and gross kinematic patterns. Seven elite male junior cross-country skiers were initially tested for peak oxygen uptake during treadmill roller ski skating in the laboratory. Thereafter, on a separate day, the skiers performed two 20-m maximal velocity tests in both uphill and flat terrain. The main experiment consisted of three 5-km of skiing with the skating technique in a competition track on snow at low- (LIT), moderate- (MIT), and high-intensity training (HIT) using a heart rate monitor and an inertial measurement unit (IMU) coupled to a global navigation satellite system (GNSS). Main findings were as follows: 1) the average racing speed, the relative heart rate and work rate increased with higher exercise intensity (P <0.05), and the differences was higher between MIT vs. LIT than MIT vs. HIT (P <0.05), 2) there was a shift in the delayed heart rate response, and the effect was larger with higher intensity, thus limiting the possibility for recovery during higher intensity, 3) more than half of the total time in all intensities was spent uphill, 4) the uphill sections were responsible for the greatest performance differences during HIT (P <0.05), 5) G2-V_{max} correlated strongly with speed uphill HIT (r = 0.78, P < 0.05). Cross-country skiing in terms of speed, external work, metabolic intensity, and kinematics are clearly interval based, which makes ski-specific training in varying terrain unique. Hence, the effect of exercise intensity must especially be taken into account during training in cross-country skiing.

Sammendrag

I langrennskonkurranser ser man at arbeidsintensiteten fluktuerer. I hvilken grad dette er gjeldende under ski-spesifikk trening på de ulike treningsintensitetene er til nå ikke kjent. Hensikten med denne studien var derfor å undersøke hastighet, puls, effekt av arbeid og kinematikk. Syv mannlige elite junior langrennsløpere ble først testet for maksimalt oksygenopptak ved bruk av skøyteknikk med rulleski på tredemølle i et laboratorium. I felt på en egen dag, utførte skiløperne to 20-maksimale hastighetstester på flatt og i bratt terreng. Hovedforsøket bestod av å gå tre 5-km runder med skøyteteknikk i en konkurranseløype på snø ved lav (LIT), moderat (MIT) og høy intensitet (HIT) ved bruk av pulsmåler, og en treghet målenhet (IMU) som var koblet til et globalt satellittnavigasjonssystem (GNSS). Hovedfunnene var som følger: En økning i treningsintensitet øker den gjennomsnittlige hastigheten, hjerteraten og effekten av arbeid (P<0.05), og forskjellene var større mellom MIT vs. LIT enn MIT vs. HIT, 2) det var en forskyvning av den forsinkede pulsresponsen og effekten var større ved høyere treningsintensitet noe som begrenset muligheten for hvile mer i HIT og MIT vs. LIT, 3) mer enn halvparten av tiden ble brukt i motbakke på alle intensiteter, 4) motbakker hadde mest å si for prestasjon under HIT, 5) G2-V_{max} korrelerte sterkt med fart i motbakke under HIT (r = 0.78, P <0.05). Langrenn i form av fart, ytre arbeid, indre intensitet og kinematikk er tydelig intervallbasert, noe som gjør at ski-spesifikk trening i ulendt terreng er unikt for idretten. Derfor må effekten av treningsintensitet tas særlig hensyn til under trening i langrenn.

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Table of contents

Introduction

Cross-country skiers compete in varying terrain and at widely varying speeds, which makes the endurance sport of cross-country skiing both physically and technically demanding (Smith 1992; Andersson et al. 2010). The duration of cross-country skiing races ranges from a few minutes to several hours depending on the distance, and the competition terrain is mandated to include approximately one-third uphill, one-third flat and one-third downhill (Sandbakk and Holmberg 2014; Hoffman and Clifford 1992). In order to maintain a high speed, skiers continuously change among and adapt their techniques according to the track topography (Bilodeau et al. 1992; Nilsson et al. 2004); however, the greatest individual performance variation is seen in the uphill sections, where work rates are increased (Welde et al. 2003; Sandbakk and Holmberg 2014; Norman and Komi 1987; Mognoni et al. 2001). These higher work rates are accompanied by higher efficiency in uphill terrain, but also higher exercise intensity as world-class skiers during a skating competition show increased heart rates during uphill sections (Bolger et al. 2015). In contrast, downhill sections are primarily used for recovery, where the exercise intensity decreases (Sandbakk et al. 2011a). However, it is not presently known whether the fluctuation in exercise intensity is present in the same manner during training and under different exercise intensities.

The fluctuations of speed, work rate and metabolic intensity are unique for cross-country skiing and is of particular interest for understanding skiers' training. The major component of the "polarized" endurance-training model utilized in this sport consists of low-intensity training (LIT), and in addition low to moderate volumes of moderate- (MIT) and high-intensity training (HIT) (Seiler and Kjerland 2006; Gaskill et al. 1999; Rusko 1987). Since skiing and roller skiing on varying terrain are the most important modes of exercise, the actual speed, work rate and heart rate fluctuations during ski-specific training at the different intensities require further examination (Sandbakk and Holmberg 2014). This might have high relevance for the subsequent physiological responses. In addition skiing at a particular intensity level in varying terrain with changing speeds, demand skiers to alter their technique in an appropriate manner.

On the basis of a gear principle, the skating techniques, which are nonplanar movements where the ski is edged during the skating stroke and at an angle to the forward direction, is classified into various subtechniques (G1-G7). The lower gears are used uphill and the higher gears are used in flat and downhill sections at higher speeds with the use of effective leg push-offs (Andersson et al. 2010). Furthermore, gear shifts and regulation of cycle length and/or the cycle rate within these gears controls the speed (Nilsson et al. 2004), and the higher the speed the more is required by the skiers to produce propulsive forces to increase cycle length (Sandbakk and Holmberg 2014).

Although previous studies have examined kinematics in the field during simulated competitions on snow (Sandbakk et al. 2011a; Andersson et al. 2010), experiments on snow (Bilodeau et al. 1992; Vahasoyrinki et al. 2008), and during competitions (Bilodeau et al. 1996; Smith and Heagy 1994), the methods have been time consuming using lapsed-time video analysis, EMG, and force cells. In contrast, micro-sensor technology has the potential for measuring kinematics, kinetics, speed, and position in real time without requiring the use of resource-intensive methods, and are being used in e.g. cycling (Paton and Hopkins 2001), swimming (Fulton et al. 2009; Dadashi et al. 2013; Dadashi et al. 2012), and fall detection in elderly persons (Allen et al. 2006).

Classification of movement patterns in both classical and skating cross-country skiing using sensor driven data has been conducted in the recent years with different and diverse approaches with promising results in terms of finding algorithms for classification purposes. Marsland et al. (2012) visually identified cyclical movement patters in both skating and classical subtechniques. In a continuation of their previous work, Marsland et al. (2015) automatically classified kinematics in classical cross-country skiing. Furthermore, statistical machine learning techniques classified skiing gears in the skating technique (Holst and Jonasson 2013; Stoggl et al. 2014), while an automated identification system based on correlation classified subtechniques in classical cross-country skiing (Sakurai et al. 2014). Moreover, Myklebust et al. (2011) identified subtechniques in the skating technique automatically without visual analysis, and the differences in timing of ski and pole actions was found in the skating technique (Myklebust et al. 2014). However, micro-sensor technology has not been adapted for kinematical analysis purposes of daily training or competition in cross-country skiing despite its great potential for performance assessment (Marsland et al. 2015).

To the best knowledge of the author’s knowledge, no previous study has directly investigated the effect of exercise intensity in the skating technique on speed and heart rate profiles, work rate and kinematics in cross-country skiing. Therefore, the aim of this study was to investigate speed, work rate, and gross kinematic patterns (i.e., cycle length and cycle rate) in elite male junior cross-country skiers while skating on snow in varying terrain during low-, moderate- and high-intensity training using heart rate and an inertial measurement unit (IMU) coupled to a global navigation satellite system (GNSS).

Methods

Subjects

Seven Norwegian male junior elite cross-country skiers (age 18.3 ± 0.5 years, body height 180 ± 6 cm, body mass 76.8 ± 6.4 kg, peak oxygen uptake 5.17 ± 0.63 $L \cdot min^{-1}$ and 67.2 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$, peak HR 193 ± 11 beats min^{-1}) volunteered to participate in the study. All protocols and procedures were explained verbally to each skier and written informed consent was obtained and signed. This study was pre-approved by the Norwegian Centre for Research Data (NSD), Bergen, Norway.

Overall design

Initially, all skiers were tested for peak oxygen uptake during treadmill roller ski skating in the laboratory. Thereafter, on a separate day, the skiers performed two 20-m maximal velocity tests in both uphill and flat terrain. The main experiment consisted of three 5-km of skiing with the skating technique in a competition track on snow at a low, moderate, and high-intensity, respectively. The skiers were investigated with respect to speed and heart rate profiles, as well as kinematics and estimated work rates using a heart rate monitor and an inertial measurement unit (IMU) coupled to a global navigation satellite system (GNSS).

Instruments and Materials

The roller-ski skating was performed on a 5 × 3-m motor-driven treadmill (Forcelink B.V., Culemborg, The Netherlands). The inclination and speed were calibrated using the Qualisys Pro Reflex system and Qualisys Track Manager software (Qualisys AB, Gothenburg, Sweden). The non-slip rubber surface of the treadmill belt allowed the subjects to use poles (Madshus UHM 100, Biri, Norway) with special carbide tips. Poles were available in five-centimeters intervals and the subjects chose the preferred length. A safety harness secured the skiers during the treadmill testing. In order to minimize variations in rolling resistance, all of the skiers used the same pair of IDT roller skating skis with standard resistance category 2 wheels (IDT Sports, Lena, Norway), and the roller skis were pre-warmed before each test with 20 min of roller skiing on the treadmill.

Respiratory parameters were measured employing open-circuit, indirect calorimetry with an Oxycon Pro apparatus (Jaeger GmbH, Hoechberg, Germany). Before each measurement, the VO_2 and VCO_2 analysers were calibrated using a mixture of gases (16.00% ± 0.04% O_2 and 5.0% ± 0.1% CO_2, Riessner-Gase GmbH & Co, Lichtenfels, Germany), and the expiratory flow meter calibrated with a 3 L volume syringe (Hans Rudolph Inc. Kansas City, MO). Heart rate (HR) was recorded with a heart-rate monitor Garmin Forerunner 920XT GPS (Garmin Ltd., Olathe, KS), with samplings rate of 1 Hz. Blood samples collected from the fingertip of the ring finger (20-μL) was analysed by Biosen C-Line lactate analyzer (EKF diagnostics GmbH, Magdeburg, Germany) and determined the blood lactate concentration (BLa). Rating of perceived exertion (RPE) was assessed using the Borg Scale (Borg 1970). The skier's body mass was measured before the treadmill test (Seca, model 708, GmbH, Hamburg, Germany) and body height was calibrated with a stadiometer (Holtain Ltd., Crosswell, UK).

Test Protocols and Measurements

Laboratory test

Maximal aerobic capacity was tested in an incremental test at 5% inclination, employing the G3 skating technique, with individually customised starting velocities of 3.9-4.7 $m \cdot s^{-1}$. The velocity was increased by 0.28 $m \cdot s^{-1}$ every min until exhaustion. The criteria for maximal effort was 1) a VO_2 plateau with increasing exercise intensity, 2) RER above 1.10, and 3) BLa exceeding 8 $mmol \cdot L^{-1}$. VO_2 was measured continuously and the average of the three highest 10-s consecutive measurements determined VO_{2peak} (Bassett and Howley 2000). The highest HR value during the test was defined as $HR_{peak.}$

Maximal velocity (V_{max}) test

A 20-m maximal velocity sprint tests on flat and uphill terrain (∼13% incline) were performed on snow using the skating G3 technique (G3-V_{max}) and the skating G2 technique (G2-V_{max}), respectively. Prior to testing the skiers warmed-up according to their own individual programs and used their own ski equipment, which was individualized to the specific skiers' racing preferences, including poles, boots and skis. All skiers were instructed to prepare and use their own skating skis for the prevailing conditions including grinds, structure and waxing. The subjects performed a self-selected run-up before the 20-m measurement zone and were instructed to reach maximal velocity when entering the measurement zone. V_{max} tests were carried out twice, each separated with 4 min of light activity. The velocity was calculated based on time from two pair of photocells (TC-Timer; Brower Timing Systems, Draper, UT, USA) placed at start and finish, 20 cm above the ground and with 250 cm between the members of each pair.

Low-, moderate- and high-intensity exercise

The subsequent cross-country skiing exercise on snow during low-, moderate- and high-intensity employing the skating technique was performed after 10 min. Valid course and elevation profiles were standardized with a Garmin Forerunner 920XT GPS (Garmin Ltd., Olathe, KS) with built in barometer for accurate elevation measurements that collected position data and elevation data at a 1 Hz. The total length of the course was 5140-m (3 x 1.713-m) with varied topography based on a course profile divided into uphill, flat and downhill sections that made up 30, 29.3 and 40.7% of the 1.7-km loop, respectively. A change between positive and negative gradient in the course profile defined the boundary between the different terrain sections, and the uphill and downhill sections were characterized by a minimum elevation difference of 10-m within the section. A section with an ascent or decent of less than 10-m was defined as flat terrain, and adjacent sections of flat terrain were merged into longer sections, which may contain small-scale uphill and downhill parts. Each lap was divided into 8 different sections S1-S8, according to terrain topography (Fig. 2-3). One lap consisted of two uphill sections (S2, S6) with mean inclines of 13% and 8%, four flat sections (S1, S3, S4, S7) and two downhill sections (S4, S7) with mean slopes of 8% and 10%. The maximal elevation difference was 32 m with a total of 62 m per lap, and the longest continuous climb was 301.8-m (S6).

The skiers were instructed to initially ski at low-intensity (Borg-scale: 8-14, LIT: 60-72% of HR_{max}), thereafter at moderate-intensity (Borg-scale 14-16, MIT: 82-87% of HR_{max}) and finally at high-intensity (Borg-scale 16-20, HIT: 87-97% of HR_{max}) with 3 min of light activity in between. Each exercise bout had 1-min interval start where drafting behind other skiers was prohibited to avoid the potential of skiers saving time and energy by drag. The skiers wore a Garmin Forerunner 920XT GPS (Garmin Ltd., Olathe, KS) that collected position data and heart rate data at a 1 Hz sampling rate. In order to ensure a low resultant inaccuracy in GPS data, this study projected the skiers position data onto a standard course and used a projection algorithm previously described by Bolger and co-workers (2015). The average projection distance from the GPS track for each skier to the corresponding point on the standard course varied between 2.1 and 4.0 meters for all the skiers and loops. Calculation of time in each terrain section was based on virtual split times. Speed was calculated by dividing the distance of a section with the time each skier used in that particular section and are presented as mean speed and $\%V_{max}$. The intensity of each exercise bout was controlled using Borg scale and heart rate data (missing data $N = 1$). Cold weather conditions with air temperature of -18°C caused missing data ($N = 5$) on blood lactate concentration (BLa) of 5 µl-samples taken from the fingertip by Lactate Pro LT-1710*t* kit (Arkray Inc., Kyoto, Japan), and are not included in this study.

Power calculations

The friction constant on snow (µ) was calculated on the basis of five deceleration-measurements. A skier (weighing a total of 74 kg with ski equipment) glided passively down a ~5 % downhill incline onto a 20-m flat zone, sitting in a tucked down position with an initial speed of 3 $m \cdot s^{-1}$. Four pairs of photocells (TC-Timer; Brower Timing Systems, Draper, UT, USA) placed 20 cm above the ground and with 100 cm between the members of each pair, were employed to determine the initial and final speeds. The loss of speed was used to calculate the deceleration and subsequently, the friction coefficient ~ 0.026 (Eq. 1), which was relatively equal before and after skiing exercise tests. The force of air drag, which was minimal at this slow speed, was ignored.

$$(\mu = \frac{\Delta a}{g \cdot \Delta T}) \qquad \text{(I)}$$

The wind drag component $A \cdot C_d$ of 0.35, incorporated in this study, was estimated from wind tunnel testing while skating on a sliding board mounted on two Kistler force plates (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland), described by Leirdal and co-workers (2006). A subject with approximately the same height and body mass as the skiers in this study was used. A 220 kW centrifugal fan propelled the wind and the test area was 12.5 m long, with a width of 2.7 m and a height of 1.8 m (Sandbakk et al. 2011a).

The work rate was calculated according to Sandbakk and co-workers (2011a), as the sum of power against gravity (P_g), friction (P_f), and air drag (P_d), with V being the average uphill (S2) and flat (S8) speed, ∝ the angle of incline, μ_s the coefficient of friction, C_d the drag coefficient, A the exposed frontal area of the skier and P the density of the air, which previously was calculated by Moxnes and co-workers (2014) (Eq. II).

$$Ptot = P_g + P_f + P_d \quad \text{(IIa)}$$

$$Ptot = m \cdot g \cdot \sin(\propto) \cdot v + (1 - 0.05) \cdot m \cdot g \cdot cos(\propto) \cdot \mu_s \cdot v + 0.5 \cdot p \cdot v \cdot A \cdot C_d \quad \text{(IIb)}$$

The work rate calculations were adjusted for body mass according to Millet et al. (1998a); (Millet et al. 1998b), because of the reduction in mean normal force on the skis during a cycle. The reduction is a result of the poling action when skiers apply their body mass to the poles and influencing P_f (Sandbakk et al. 2011a).

The weather was stable during the entire test day with light-wind, air temperature of -18°C, snow temperature of -19°C and relative air humidity of ~50%. The track was hard packed with mixed snow and machine-prepared in the morning prior to testing.

Data processing

The sensor unit used in this study is a single 9-axis Apertus IMU (Apertus Skiing Sensor, Apertus AS, Asker, Norway) with integrated barometry, built up by an accelerometer, a gyroscope and a magnetometer, where one of these axes are being used – namely the accelerometer data (accelerometer y-axis), which detects lateral movement of the hip. The Apertus IMU was centrally placed above the lower spine of the skier. Data was transmitted in real-time by Bluetooth, using a mobile phone (Sony Xperia Z3 compact, Sony Inc., Tokyo, Japan) located in a bib-vest (Trimtex, Lillesand, Norway), which received and stored the collected data for post processing in Matlab R2014$_b$ (The MathWorks Inc., Natick, MA).

The raw signal data was processed, including filtering, cycle detection, and normalization of data, previously described by (Meland 2016). Two variants of a simple averaging filter consisting of a convolution with a Gaussian were used: One for generally reducing high frequency noise while retaining the significant features of the movement of the skier, the other for very low frequencies to identify the cycles of the movement. The high frequency filter utilizes a standard deviation of 90 ms on the Gaussian, and the low frequency a standard deviation of 600 ms. The peaks in the low frequency signal are used for cycle detection through cutting the raw signal up in segments corresponding to these identified cycles, as shown in Fig 1. In order to standardize the cycles for left- and right-domination all cycles were converted into absolute values and shifted according to the half-period offset, which detects shifted cycles through the minimas of the sinusoidal harmony instead of the maximas. In that way, all cycles are represented in the same manner (Meland 2016).

In the current study, the kinematical analyses of the uphill (S2) and the flat terrain (S8) were based on analyses of four elite junior cross-country skiers (N = 3 missing data) during the entire terrain segment. One movement cycle in the G2 and G3 skating technique was defined as a complete left and right leg stroke, together with an asymmetrical poling action on every second leg stroke and one poling action for every leg stroke, respectively. Cycle time was determined as the average time between two pole plants during cycles in the analysed section. Cycle length was calculated as the mean speed multiplied by the cycle time and the cycle rate was the reciprocal of cycle time.

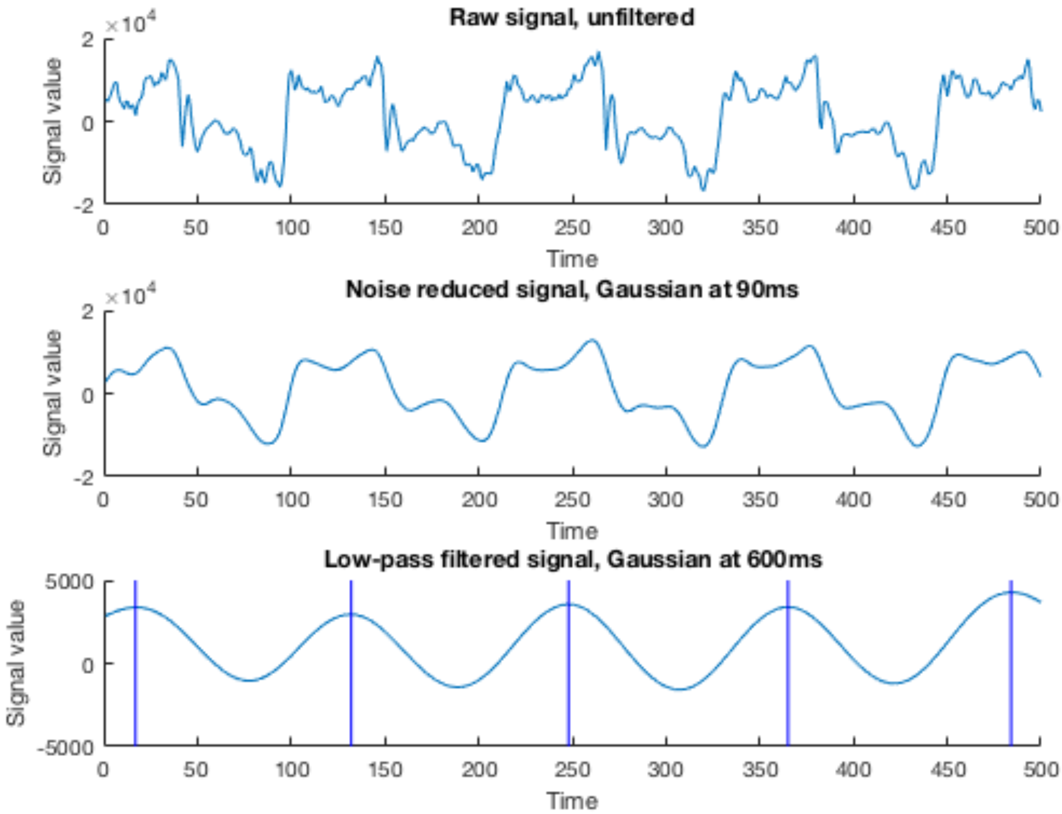

Figure 1 An illustration of a raw signal filtered by two different convolutions with a Gaussian. The lower plot illustrates results of cycle detection on the low pass filtered signal (Meland 2016)

Statistical Analyses

All data were shown to be normally distributed with a Shapiro–Wilks test (except) and are presented as means and standard deviations (± SD). Some variables are presented with range. In order to assess relationships between variables, a bivariate Pearson's product–moment correlation coefficient test was performed. A one-way repeated measures ANOVA with a Bonferroni post hoc test was run to determine the effect of different exercise intensities. The coefficient of variation ($SD \cdot mean^{-1}$) · 100% within each section was also calculated. The statistical significance level was set at $P < .05$. All statistical tests were processed using IBM SPSS statistics version 23 Software for Mac (SPSS Inc., Chicago, IL, USA) and Office Excel 2011 (Microsoft Corporation, Redmond, WA, USA).

Results

The skiers' mean total racing time was 1238 ± 34 s (1217-1312), 961 ± 52 (896-1057), 874 ± 48 (832-958), resulting in mean speed ($m{\cdot}s^{-1}$) of 4.2 ± 0.1 (3.9-4.2), 5.4 ± 2.3 (4.9-5.7), 5.9 ± 0.3 5.8-6.2) for LIT, MIT and HIT, respectively. The periods of the total racing time on the uphill, flat and downhill terrains were ~ 57.2%, 22.3%, 20.5% for LIT, 53.8%, 22.9%, 23.3% for MIT, and 51.7%, 23.3%, 25.0% for HIT, respectively. The mean speed ($m{\cdot}s^{-1}$) and speed differences between the respective exercise intensities throughout the course are illustrated in Fig. 2. Mean speed increased with higher intensity $F(1.164, 6.985) = 129.712$, $P < 0.001$, $\varepsilon = .582$. Post hoc analysis with a Bonferroni adjustment revealed that the speed was different between all intensities in all terrains, except MIT vs. HIT in flat terrain ($P < 0.05$).

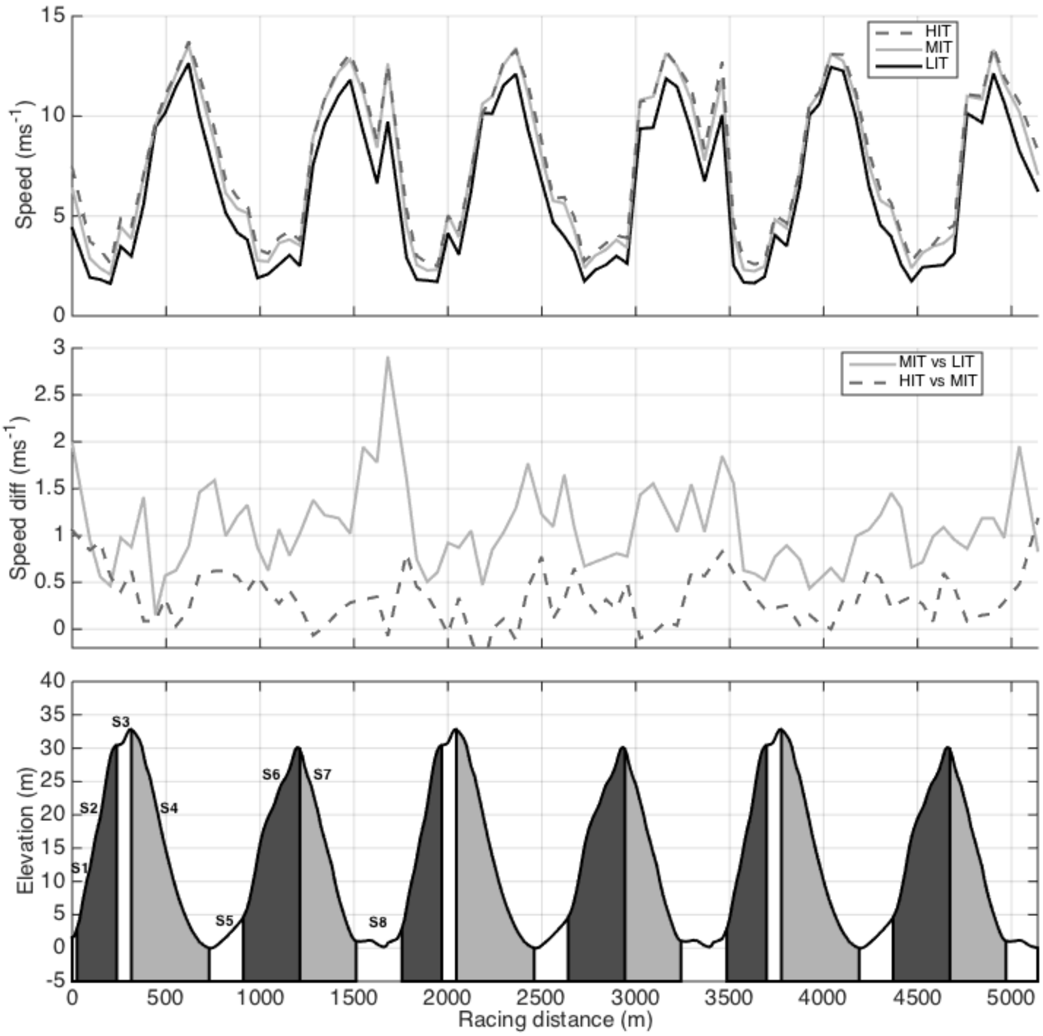

Figure 2 Mean speeds in different sections of terrain and difference in mean speed between intensities for seven elite male junior cross-country skiers while skating at low- (LIT), moderate- (MIT) and high-intensity (HIT).

The mean maximal speed in the 20-m G3-V_{max} and G2-V_{max} tests are shown in Table 1, with the highest and lowest speed achieved during flat and uphill, respectively.

The detailed heart rate profile of $\%HR_{peak}$ and difference between the respective exercise intensities throughout the course are illustrated in Fig. 3. The skiers had relatively higher heart rate with higher intensity $F(1.009, 5.046) = 27.547$, $P < 0.05$, $\varepsilon = .505$. The skiers' mean and peak heart rate were 151 ± 19 and 188 ± 19, 172 ± 11 and 193 ± 11, 178 ± 9 and 195 ± 9 beats min^{-1}, corresponding to 77 and 96% of $HR_{peak,}$ 87 and 98% $HR_{peak,}$ 90 and 99% of $HR_{peak,}$ for LIT, MIT, and HIT, respectively. The Borg-scale values after the exercise bouts were 9.6 ± 1.9, 14 ± 0.8 and 17.9 ± 1.1 for LIT, MIT and HIT, respectively.

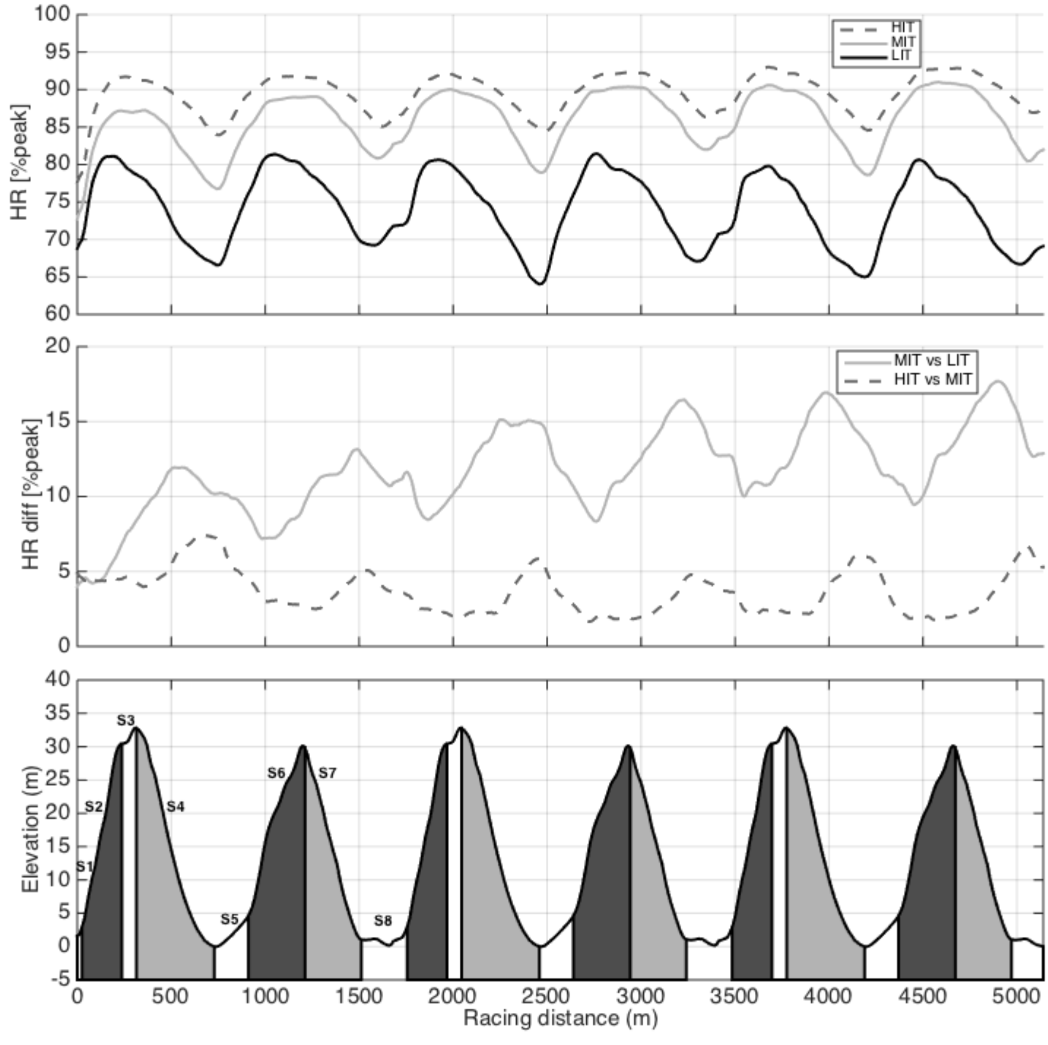

Figure 3 Mean heart rate [%peak] in different sections of terrain and difference in mean heart rate [%peak] between intensities for seven elite male junior cross-country skiers while skating at low- (LIT), moderate- (MIT) and high-intensity (HIT)

Estimated work rates (Eq. II), maximum work rate (WR_{max}) and speed compared to maximum velocity (%Vmax) in both terrains (S2, S8) during lap 3 for all intensities (N = 7) are presented in Table 1. Work rate increased with higher intensity in uphill $F(3, 18) = 242.793$, $P < 0.001$, and in flat $F(1.288, 7.729) = 21.627$, $P < 0.001$. Post hoc analysis with a Bonferroni adjustment revealed that the work rate was different between all intensities ($P <$ 0.05. The skiers mean heart rate data for the corresponding analysed segments was 78.2, 89.1, 91.6% of HR_{peak} for uphill (S2), and 68.1, 82.5, 86.9 % of HR_{peak} for flat (S8), respectively.

Table 1 Changes speeds and work rates in specific intensities during lap 3 and maximum velocity tests for seven elite male junior cross-country skiers while skiing with the G2 skating technique uphill (S2) and the G3 skating technique flat (S8)

Parameters	Exercise intensity				
	Terrain	Low	Moderate	High	V_{max}
Speed ($m·s^{-1}$)	Uphill	1.8 ± 0.1	2.5 ± 0.2*	3.0 ± 0.3$^{*, \#}$	4.9 ± 0.3$^{*, \#, a}$
	Flat	5.9 ± 0.2	6.9 ± 0.5	7.3 ± 1.2*	8.8 ± 0.4$^{*, \#, a}$
Speed CV (%)	Uphill	4.82	7.83	10.85	5.22
	Flat	4.01	7.40	16.19	4.45
$\%V_{max}$	Uphill	37.4	51.9	60.4	100.0
	Flat	67.0	78.2	82.6	100.0
Work rate (W)	Uphill	213 ± 24	298 ± 27*	349 ± 54$^{*, \#}$	594 ± 62$^{*, \#, a}$
	Flat	200 ± 21	252 ± 19*	282 ± 79$^{*, \#}$	382 ± 28$^{*, \#, a}$
Work rate CV (%)	Uphill	11.04	9.19	15.46	10.38
	Flat	10.26	7.48	28.14	7.38
$\%WR_{max}$	Uphill	35.9	50.2	58.8	100.0
	Flat	52.4	66.0	73.8	100.0

N = 7 and the values are expressed as means ± SD
CV Coefficient of variation
V_{max} Maximum velocity
WR_{max} Maximum work rate
* Significantly different from the corresponding value for low intensity
$^{\#}$ Significantly different from the corresponding value for moderate intensity
^{a} Significantly different from the corresponding value for high intensity

The cycle rate and cycle length with the various speeds and two inclines for the respective exercise intensities ($N = 4$) are shown in Table 2. Cycle length was elevated by increasing speed on uphill terrain $F(3, 9) = 79.825$, $P < 0.001$. Post hoc analysis with a Bonferroni adjustment revealed that the cycle length was different between all intensities in uphill terrain, except MIT vs. HIT in uphill terrain ($P < 0.05$. In comparison, the skiers performed the longest cycle length on flat terrain during MIT, and longer cycle length during LIT and MIT vs. HIT ($P < 0.05$).

Cycle rate uphill was elevated by increasing speed on uphill terrain $F(3, 9) = 36.577$, $P < 0.001$. Post hoc analysis with a Bonferroni adjustment revealed that the cycle rate was different between all intensities in uphill terrain ($P < 0.05$). Cycle rate flat was higher during HIT vs. V_{max} ($P < 0.05$).

The skiers performed 14.3% and 8.3% higher cycle rate during MIT vs. LIT and HIT vs. MIT in uphill terrain, respectively ($P < 0.05$). In addition, the skiers performed in flat terrain 13.5% and 8.25% higher cycle rate during MIT vs. LIT and HIT vs. MIT, respectively ($P < 0.05$).

Table 2 Kinematics were analysed in specific intensities during lap 3 and maximum velocity tests for four elite male junior cross-country skiers while skiing with the G2 skating technique uphill (S2) and the G3 skating technique flat (S8)

Parameters	Exercise intensity				
	Terrain	Low	Moderate	High	V_{max}
Speed (m·s^{-1})	Uphill	1.9 ± 0.1	2.6 ± 0.1*	3.0 ± 0.3$^{*, \#}$	4.8 ± 0.2$^{*, \#, a}$
	Flat	5.9 ± 0.1	7.2 ± 0.1	7.2 ± 1.4*	8.9 ± 0.2$^{*, \#, a}$
Cycle length (m)	Uphill	2.9 ± 0.2	3.4 ± 0.1*	3.6 ± 0.1*	5.0 ± 0.32$^{*, \#, a}$
	Flat	7.8 ± 0.3$^{\#, a}$	8.2 ± 0.4^{a}	7.4 ± 1.2	9.51 ± 1.25$^{*, \#, a}$
Cycle length CV (%)	Uphill	5.51	1.80	2.55	6.32
	Flat	4.15	4.52	15.50	13.13
Cycle rate (Hz)	Uphill	0.66 ± 0.01	0.77 ± 0.04*	0.84 ± 0.06$^{*, \#}$	0.97 ± 0.05$^{*, \#, a}$
	Flat	0.77 ± 0.02	0.89 ± 0.05	0.97 ± 0.04^{b}	0.95 ± 0.10$^{*, \#}$
Cycle rate CV (%)	Uphill	1.96	5.02	7.56	4.82
	Flat	2.09	5.15	4.13	10.95

N = 4 and the values are expressed as means ± SD

V_{max} Maximum velocity

* Significantly different from the corresponding value for low intensity

\# Significantly different from the corresponding value for moderate intensity

a Significantly different from the corresponding value for high intensity

b Significantly different from the corresponding value for V_{max}

Correlations between speed in uphill and flat sections versus mean speed HIT were $r = 0.97$ and $r = 0.90$, both $P < 0.01$, whereas no correlation was found for speed downhill. Speed in uphill (S2) lap 3 and racing time HIT correlated negatively ($r = -0.87$, $P < 0.05$), whereas no correlation was found for speed in flat (S8). Cycle length correlated positively with speed in flat terrain (S8) ($r = 0.99$, $P < 0.01$) and a tendency was observed between cycle rate and speed uphill (S2) ($P < 0.07$). Speed in uphill terrain HIT and flat terrain HIT correlated positively with cycle rate (HIT) ($r = 0.97$ and $r = 0.92$, both, $P < 0.05$). Speed in uphill terrain (S2) during HIT lap 3 and G2-V_{max} correlated positively ($r = 0.78$, $P < 0.05$), whereas no relationship was found between G3-V_{max} and speed in flat (S8). No relationship was found between VO_{2peak} and the parameters of speed in different terrain and total racing time HIT.

Discussion

The present study investigated the effect of exercise intensity in the skating technique on speed and heart rate profiles, work rate and kinematic patterns (i.e., cycle length and cycle rate) in elite male junior cross-country skiers while skating on snow in varying terrain during low-, moderate- and high-intensity training. The main findings were as follows: 1) the average racing speed, the relative heart rate and work rate increased with higher exercise intensity (P <0.05), and the differences was higher between MIT vs. LIT than MIT vs. HIT (P <0.05), 2) there was a shift in the delayed heart rate response, and the effect was larger with higher intensity, thus limiting the possibility for recovery during higher intensity, 3) more than half of the total time in a all intensities was spent uphill, 4) the uphill sections were responsible for the greatest performance differences during HIT (P <0.05), 5) G2-V_{max} correlated strongly with speed uphill HIT (r = 0.78, P < 0.05).

The present investigation has revealed that elite male junior skiers consistently attained higher speeds, heart rate and work rate with higher exercise intensity in both terrains. However there was a considerable higher difference between MIT vs. LIT than MIT vs. HIT on speed, heart rate (see Fig. 2-3) and work rate (see table 1), in both terrains. Considering the high amount of volumes of training hours in LIT for cross-country skiers, it is noteworthy that LIT is so different in this aspect. Furthermore, a considerable fluctuation in speed and heart rate was seen in all intensities in both terrains, with the greatest effect on uphill terrain. This is primarily due to the nature of skiing in varying terrain where skiers' work at higher work rates in uphill compared to downhill due to relatively large work against gravity(Sandbakk et al. 2012). Previously, skiers' work rate have been estimated to be approximately 160% of the skiers' peak aerobic power when skiing in uphill terrain (Sandbakk et al. 2011a), which is supported by earlier studies of world-class skiers (Norman and Komi 1987; Norman et al. 1989). Despite the intense work rate in uphill terrain, the metabolic intensity in cross-country skiing is also affected by lower work rates on flat and downhill terrain (Sandbakk et al. 2011a); Norman and Komi (1987). Sandbakk et al. (2011a) suggest that downhill sections might exert an indirect impact on performance since skiers primarily use downhill sections for recovery and thereby enabling them to generate more pronounced anaerobic power when skiing uphill.

The aspect of utilizing downhill sections for recovery was clearly seen in the heart rate profile (see Fig. 3). The increased intensity during uphill skiing had a delayed heart rate response, which was displayed in the beginning of the following flat or downhill sections. Hence, higher intensity leads to a shift in the delayed heart rate response, thus limiting the possibility for recovery during higher intensity. This observation has also been seen in world-class skiers during a skating competition (Bolger et al. 2015). Furthermore, when looking more detailed into heart rate profiles in cross-country skiing, the average heart rate data does not solely reflect the skier's work in the different terrain sections.

The skiing times spent on the uphill, flat and downhill sections during all exercise intensities in this study are in correspondence with previous observations of that more than half of the total time in a distance cross-country skiing race is spent uphill (Bergh and Forsberg 2000; Bolger et al. 2015). Hence, the results confirm that the skiers were tested in competition-specific terrain on snow. In the present study, HIT simulated a cross-country skiing race and the skiing times on the uphill sections where the main determinants for the race's results, followed by the time spent on the flat sections, whereas no correlation was observed regarding the downhill sections. The importance of uphill skiing for overall performance has previously been observed in connection with both distance and sprint skiing (Andersson et al. 2010; Welde et al. 2003; Bergh and Forsberg 2000; Sandbakk et al. 2011a). Speed in downhill sections for all exercise intensities was not correlated with skiing times, which is in agreement with previous studies (Bolger et al. 2015; Sandbakk et al. 2011a; Andersson et al. 2010).

In the present study, the strong negative correlation between G2-V_{max} and HIT performance reported here illustrates the general importance of high-speed ability for race performance, as also demonstrated in a previous study (Sandbakk et al. 2011a). No relationship was found between G3-V_{max} and velocity in flat (S8). The lack of correlation between VO_{2peak} and skiing performance observed here differs from findings previously reported in cross-country skiing (Sandbakk et al. 2011a; Sandbakk et al. 2010, 2011b). However, the subjects in this study are junior skiers, and it is likely that they have not developed their maximum oxygen capacity yet.

In order to examine in greater detail the relationship between performance on uphill terrain and flat terrain, the uphill section (S2) and the flat section (S8) were analysed more closely. Cycle length and cycle rate were obtained with the use of accelerometer data, and the main effects of intensity was that cycle length was significantly elevated by increasing speed uphill, except in MIT vs. HIT where the mean speed was nearly equal. In comparison the skiers performed the longest cycle length during MIT on flat terrain, consequently by higher mean speed. The contribution of cycle rate was significantly higher in uphill terrain, whereas the skiers had significantly highest cycle rate during HIT flat with associated lower speed and cycle length reached compared to V_{max} with lower cycle rate and higher speed and cycle length. The observation of that cycle length increases with speed are in agreement with other studies (Bilodeau et al. 1996; Rundell and McCarthy 1996). However, that the highest cycles rates were used in the high velocity technique of G3, rather than in G2 are an inverse pattern compared to observations of Andersson et al. (2010). However, the uphill was steep (~13%), which led to a significantly lower speed ($P < 0.05$).

The main limitation of the current study can be found in the accuracy of the global navigation satellite system (GNSS) position data, which was used to calculate speed. The accuracy in the calculation of time spent on a given section of a course using GPS position data decreases when the length of the section decreases. The present study used a GPS device that simultaneously tracked both Russian GLONASS and GPS satellites, which doubles the number of satellites (Takac et al. 2005), improving the accuracy compared to non-GLONASS systems. Moreover, the calculation of V_{ski} (=v/(cos(orientation angle)) was not incorporated into the calculations of P_f in this study. Instead, the mean speed in the direction of travel was used, which has a lower resultant speed than skis angled relative to the direction of the travel. However, the different calculations of skiing speed constitute marginal differences. Another limitation was the missing data of blood lactate. However, the heart rate data and Borg-scale values were within the boundaries of the respective intensity zones, and these values corresponds to values of blood lactate with regard to measure and evaluate intensity (Scherr et al. 2013). A further development of this study would be to additionally reveal technique distributions with the use of algorithms that auto classifies subtechniques both in skating and classical cross-country skiing.

In conclusions, the current study show that cross-country skiing in terms of speed, external work, metabolic intensity, and kinematics is clearly interval based, which makes ski-specific training in varying terrain unique. Hence, the effect of exercise intensity must be considered in the skiers' training distribution and exercise program.

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