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Performance Effects of Video- and Sensor-Based Feedback for Implementing a Terrain-Specific Micropacing Strategy in Cross-Country Skiing

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Purpose: To investigate the performance effects of video- and sensor-based feedback for implementing a terrain-specific micropacing strategy in cross-country (XC) skiing. ***Methods:*** Following a simulated 10-km skating time trial (Race1) on snow, 26 national-level male XC skiers were randomly allocated into an intervention (n = 14) or control group (n = 12), before repeating the race (Race2) 2 days later. Between races, intervention received video- and sensor-based feedback through a theoretical lecture and a practical training session aiming to implement a terrain-specific micropacing strategy focusing on active power production over designated hilltops to save time in the subsequent downhill. The control group only received their overall results and performed a training session with matched training load. ***Results:*** From Race1 to Race2, the intervention group increased the total variation of chest acceleration on all hilltops ($P < .001$) and reduced time compared with the control group in a specifically targeted downhill segment (mean group difference: –0.55 s; 95% confidence interval [CI], –0.9 to –0.19 s; $P = .003$), as well as in overall time spent in downhill (–14.4 s; 95% CI, –21.4 to –7.4 s; $P < .001$) and flat terrain (–6.5 s; 95% CI, –11.0 to –1.9 s; $P = .006$). No between-groups differences were found for either overall uphill terrain (–9.3 s; 95% CI, –31.2 to 13.2 s; $P = .426$) or total race time (–32.2 s; 95% CI, –100.2 to 35.9 s; $P = .339$). ***Conclusion:*** Targeted training combined with video- and sensor-based feedback led to a successful implementation of a terrain-specific micropacing strategy in XC skiing, which reduced the time spent in downhill and flat terrain for intervention compared with a control group. However, no change in overall performance was observed between the 2 groups of XC skiers.

Keywords: GNSS, pacing, IMU, sensor performance, XC skiing

Cross-country (XC) skiing is an endurance sport performed outdoors in varying terrain and cold conditions, with competition formats ranging from 3-minute sprint races to 2-hour distance races. The race courses consist of ascending, flat, and descending terrain, designed so each of these sections is relatively short and lasts for less than a minute (typically ranging between 10 s and 35 s).[1] Accordingly, XC skiing involves constant variations in speed, external power, metabolic intensity, as well as frequent transitions between various subtechniques of the skating and classical style, and modification of cycle rate and length according to the course topography, conditions, and race dynamics.[2,3] Since all these parameters interplay, XC skiing is not only dependent on endurance capacity but also on technical and tactical skills.[2]

An essential factor in endurance competitions is to optimize the pacing strategy, that is, to use energetic resources as effectively as possible from start to finish.[4] The varying terrain in XC skiing requires a continuous decision-making process based on anticipation of effort, information about the course profile and snow conditions, as well as perception of the current physiological and psychological state. Accordingly, XC skiers employ a variable pacing pattern with higher metabolic rates and power production during uphill than flat and downhill terrain,[5,6] with the uphill sections being the most performance determining terrain.[7–10] To further improve performance, refining XC skiers' micropacing strategy, by adjustments of speed and/or transitions between subtechniques within or between terrain sections, can be beneficial. Still, only 2 previous studies have investigated different aspects of micropacing in XC skiing. A recent intervention study by Losnegard et al[11] found that skiers with a high start speed improved performance by employing a more even pacing strategy. Furthermore, Ihalainen et al[12] investigated micropacing strategies during a classical sprint time trial and showed that the instant speed during the acceleration phase over hilltops was

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significantly correlated with speed in the subsequent downhill section. This study also indicated that performance in downhill terrain influences overall performance, which is especially relevant when the margins between skiers are small.[12] Therefore, we hypothesize that increasing speed over specific hilltops to save time in the subsequent downhill without reducing speed in other parts of the track could improve XC skiing performance.

XC skiers typically perform training sessions on the specific race courses prior to competitions to optimize technical and tactical solutions. Still, the pacing strategies developed in such sessions are typically based on the experiences of the athlete and coach. In this context, objective feedback would be valuable for helping athletes and coaches to optimize micropacing strategies and thereby improve performance in the upcoming competition. Currently, objective feedback on speed and technical patterns can be gained from the combined use of various sensors with adapted signal processing and smart classification and detection models.[13–16] This could be combined with video that is recently reported as a promising tool for improving individual feedback when coaching large groups.[17] Therefore, the aim of this study was to investigate the performance effects of using video- and sensor-based feedback for implementing a terrain-specific micropacing strategy when preparing for an XC skiing competition.

Methods

Participants

Twenty-six (junior and senior) male skiers, classified as highly trained/national-level (Tier 3) athletes according to a recently developed classification framework,[18] volunteered to participate in the study and completed the protocol. The skiers were recruited from a high-school and university with a specialized study program for XC skiing in mid-Norway and had 6–10 years of experience as skiers (participant characteristics presented below).

Since the Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies, the study was performed in accordance with the institutional requirements and in line with the Helsinki declaration. Approval for data security and handling was obtained from the Norwegian Center for Research Data (project number 700549) in front of the study. Prior to commencing the study, all skiers provided written informed consent to voluntarily take part in the study and were informed that they could withdraw at any time point.

Design

The study was performed in Meråker in an International Ski Federation–homologated sprint course (Grova, altitude 408 m.a.s.l) in April 2021. The skiers performed 2 simulated 10-km time-trial races (Race1 and Race2) in the skating technique separated by 48 hours. The competition consisted of 3 laps of 3.2 km and was performed with a self-selected lap-to-lap pacing strategy (ie, macropacing). The race course exhibited a varied topography based on a course profile divided into uphill (38%), flat (17%), and downhill (45%) sections, with a total climb of 306 m (3 × 102 m) (Figure 1). To avoid too many skiers in the course at the same time, a 5-minute start interval was used between skiers. After the first 15 skiers, there was a 30-minute break due to the number of available sensors. Prior to both races, the skiers performed warm-up procedures consisting of 1 lap of 3.2 km low-intensity skiing before performing two 20-m maximal speed (V_{max}) tests in flat terrain, followed by two 20-m V_{max} tests in uphill terrain.

Intervention

After Race1, the skiers were randomly allocated into an intervention group (INT, n = 14, 20 [1] y, 78 [9] kg, 182 [8] cm, VO_2peak skate = 71.5 [4.5] mL·min^{-1}·kg^{-1}) or control group (CON, n = 12, 19 [1] y, 77 [1] kg, 183 [1] cm, VO_2peak skate = 72.4 [3.5] mL·min^{-1}·kg^{-1}), see Talsnes et al[19] for VO_2peak skate protocol. The groups were balanced for starting time, performance in segment 10 (S10; see Figure 1), and race performance; difference in total race time in Race1 for INT compared with CON was +9.7 s; 95% confidence interval (CI), −60 to 79.7 s; $P = .381$. Between races, INT received video- and sensor-based feedback through both a theoretical and a practical training session, while CON only received race results and performed a training session with the same duration and intensity, but no feedback on micropacing.

In the 45-minute theoretical group session, the speed profile (measured by GNSS) in S10 of each skier was shown along with the corresponding speed profile of the fastest skier (see example of slide in Figure S1 in the Supplementary Material [available online]). Subsequently, video footage of the first part of the same segment was shown for each skier, with a brief discussion with the skier on the potential technical and tactical improvements.

In the practical training session, the skiers performed S10 7 times and S12 6 times with different technical and tactical strategies, aiming to increase speed in the specific segments but without reducing speed in other parts of the track. Here, the skiers were instructed to perform a short acceleration phase on the hilltop with a focus on active propulsion in the last cycles before quickly going down in a tucked position. Immediately after each trial, the skiers got feedback on their speed from the photocells and technical performance based on visual observation from a coach. In the first and sixth trial for S10, and in the first trial for S12, they were instructed to simulate their strategy in Race1. During their final trial in both segments, they were instructed to employ what they had learned during the practical session and ski as they planned to do in Race2. The rest of the trials were used to practice different micropacing strategies. Results from the practical training session are provided in Table S1 in the Supplementary Material (available online).

Weather and Snow Conditions

The race course was machine groomed at the same time in the morning of all 3 days. Wind, air temperature, humidity, and atmospheric pressure were measured 3 times during each race using a local weather station (https://embed.metnet.no/?dash=Fh62OYQaAI). The weather at the stadium varied as follows during Race1: wind, 1.0 to 2.2 m·s^{-1}; air temperature, −1°C to 1.6°C; relative humidity, 98% to 88%; and atmospheric pressure, 102 to 1027 hPa, and Race2: wind, 0.0 to 3.0 m·s^{-1}; air temperature, 1.5°C to 6.0°C; relative humidity, 89% to 67%; and atmospheric pressure, 1037 to 1036 hPa. Snow friction was not measured throughout the races, but based on the overall results there was a lower friction coefficient during Race2 compared with Race1, which resulted in significantly higher speeds and better overall performances during Race2. The conditions also changed within both days, with light snow falling during parts of Race1 and the sun peeking through the skies during parts of Race2.

Instruments and Materials

The skiers used their own ski equipment, including poles, boots, and skis individualized to their preferences. They were instructed to prepare the skis with the same waxing ahead of each race.

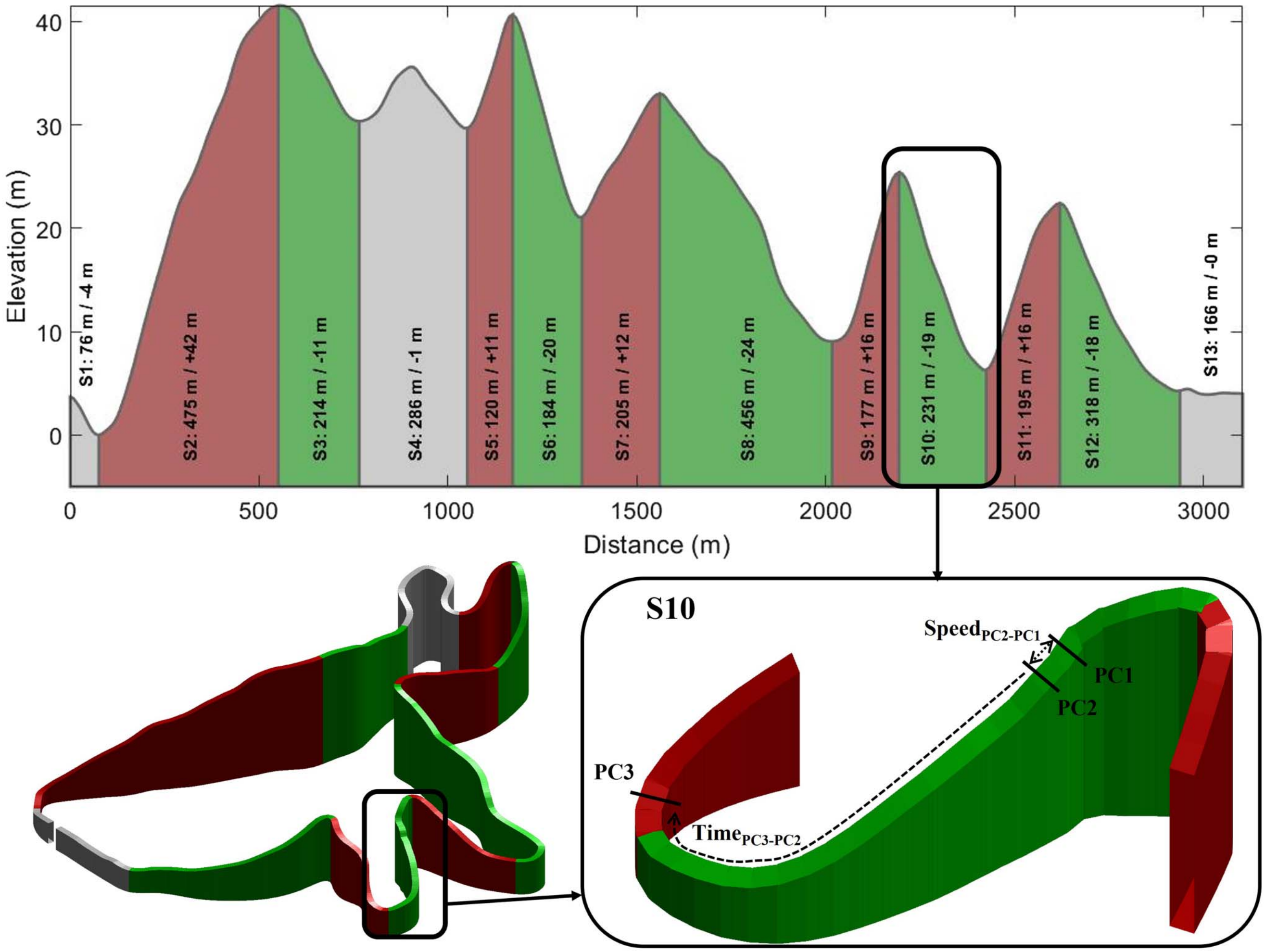

Figure 1 — The racecourse (3 × 3.2 km) used in both races in 2D divided into segments, in 3D and downhill segment 10 with placement of PCs and definition of the 2 derived measures from photocells; Speed $_{PC2–PC1}$ and $Time_{PC3–PC2}$. PC indicates photocell.

Course and elevation profiles (Figure 1) were determined with a differential global navigation system (Alpha-G3T, Javad GNSS Inc). Dual-frequency (L1 and L2) GPS and GLONASS signals were logged at 25 Hz, and a short baseline kinematic carrier phase differential GNSS solution was calculated using Justin (Javad GNSS Inc) postprocessing software.[20] Positions were smoothed using the differential GNSS solutions accuracy estimates as weighted into a spline filter.

During the races, each skier was equipped with a global navigation satellite system standalone receiver[21] (Optimeye S5, Catapult Sports) worn in a customized bib on the torso in an erect position that collected position at a sampling rate of 10 Hz. Garmin Forerunner 920XT/935 (Garmin Ltd) with an electrode belt measured heart rate at a sampling frequency of 1 Hz and is given as the percentage of HR_{max}, the highest heart rate obtained during the tests. Movement data of the chest were collected by an inertial measurement unit (IMU) fastened with velcro on the front of the electrode belt (GaitUp SA) and comprised of a 3D-accelerometer and 3D-gyroscope at 256 Hz, and a barometric pressure sensor at 64 Hz. Ratings of perceived exertion (RPE) were recorded with the 6- to 20-point Borg scale[22] immediately after the race.

During both races and in the practical training session, the performance in S10 was calculated based on photocell (PC) measurements obtained from a 2-way mesh radio transceiver (HC Timing, wiTiming) with 3 sets of 500-mW transmitters (HC Timing, wiNode), see Figure 1 for positions of the transmitters. Two measures were derived from the transmitters: (1) instant speed after the acceleration phase calculated by measuring the time in a 3-m segment ($Speed_{PC2–PC1}$) and (2) elapsed time from the speed measurement to the end of the downhill, that is, approximately the time the skier was in tucked position ($Time_{PC3–PC2}$). In addition, video of each skier passing S10 during the races was captured with video camera.

A different set of photocells (TC-Timer, Brower Timing Systems) was used to measure V_{max} flat, V_{max} uphill as well as the instant speed after the acceleration phase in S12 ($Speed_{PC2–PC1}$) during the practical training session.

Measurements and Data Exploration

Synchronization of Continuous Sensor Data. All IMU data were logged and time-synchronized during the protocol and later downloaded and analyzed offline in MATLAB (MathWorks). The IMU data from GaitUp and the GNSS sensor data from Catapult were synchronized by cross-correlating acceleration/gyroscope data recorded by the IMUs in both sensor systems. In addition, the heart rate data were correlated to the IMU data by cross correlation of the barometric sensor data in the GaitUp IMU and the Garmin watch.

Division in Downhill, Flat, and Uphill Terrain. The race course was divided into uphill, flat, and downhill terrain based on position and altitude data from DGPS measurements collected along the course, following the procedure described in Sandbakk et al.[9]

Total Variation of Chest Acceleration on Hilltops (totVarAcc). An accelerometery-derived measure that captures the intensity of both active poling and leg kick was used as an indicator of skier's biomechanical work intensity on the hilltops. The measure was based on the nonconstant part of the acceleration total signal power from the chest and is given by the following equation:

$$\text{totVarAcc} = \sum_{a\epsilon(x,y,z)} \left\{ \frac{1}{\text{N}} \sum_{i=1}^{\text{N}} \text{movvar}(a,\omega)_i \right\}.$$

Here a is the acceleration in the x,y,z-direction, N is the number of accelerometer samples, and movvar (MATLAB-function) is the gliding variance with window size $\omega = 5$ s—see Supplementary Material (available online) for details. The hilltop was defined from start of segment to the point where all subjects had transferred into tucked position determined for each hilltop by inspection of accelerometer data (S3 = 120 m, S6 = 60 m, S8 = 100 m, S10 = 100 m, S12 = 100 m).

Statistical Analysis

Shapiro–Wilk tests and comparison of histograms were used to assess the normality of the distributions of the variables, and Levene test was used to assess the homogeneity of variances in the different groups. An independent-sample t test was used for assessing between-group differences in relative change of total race time from Race1 to Race2 and for INT compared with CON. A paired t test was used to compare heart rate (mean [SD]) and Wilcoxon signed-rank test to compare RPE (median [interquartile range]) from Race1 to Race2. A linear mixed model with lap number (laps 1–3) and group/race day (with a common baseline on Race1; ie, Race1_All, Race2_INT, Race2_CON) as fixed factors and skier ID as a random factor was used to compare the relative change from Race1 to Race2 for INT compared with CON in the following parameters: $\text{Speed}_{\text{PC2–PC1}}$, $\text{Time}_{\text{PC3–PC2}}$, totVarAcc, time in S1:S13, the overall time in downhill, flat, and uphill terrain and the whole lap. Output parameters from the linear mixed model are reported as: (mean difference in improvement for INT versus CON; 95% CI, low to high; P value). Correlation between changes in performance for the skiers in INT from Race1 to Race2 ($\Delta\text{Speed}_{\text{PC2–PC1}}$, $\Delta\text{Time}_{\text{PC3–PC2}}$, ΔRacetime, and ΔtotVarAcc) with VO_2peak skate and different race measures were calculated using Pearson correlation coefficient. For all relative group comparisons, the value for CON was set at 100%, and for all analyses, the level of statistical significance was set at $\alpha = .05$. RStudio version "2021.09.1 Build 372" with the 2 libraries "lme4" and "foreign" were used for linear mixed model analysis, while SPSS (version 26.0) was used for normality assessments, t test, Wilcoxon test, and regression analysis.

Results

Performance in the Specific Downhill Segment (S10)

Due to faster external conditions in Race2, all skiers had higher speed in Race2 compared with Race1 (Figures 2 and 3). However, the reduced time per lap from Race1 to Race2 in S10 was significantly higher in INT compared with CON: Time_{S10} (–0.55 s; 95% CI, –0.9 to –0.19 s; $P = .003$), $\text{Speed}_{\text{PC2–PC1}}$ (0.74 m·s^{-1}; 95% CI, 0.53 to 0.94 m·s^{-1}; $P = .000$), and $\text{Time}_{\text{PC3–PC2}}$ (–0.63 s; 95% CI, –1.02 to –0.25 s; $P = .001$). With all 3 laps included, INT improved in total 1.65 seconds (7.5%) compared with CON in S10. The continuous speed plot (Figure 2) displays similar speed in both groups in Race1, while a substantial higher speed in INT versus CON occurs during the first part of the downhill and rest of the section in Race2.

TotVarAcc in S10 increased more for INT than CON from Race1 to Race2, the increase for INT compared with CON was 6.18 (m·s^{-2})^2 (95% CI, 4.48 to 7.87 [m·s^{-2}]^2; $P < .001$), see Figure 4 for individual values for each skier.

The improvement for the skiers in INT for $\text{Speed}_{\text{PC2–PC1}}$ ranged from 0.8 to 2.5 m·s^{-1} (9.4%–26.6%) and for $\text{Time}_{\text{PC3–P2}}$ from 2.0 to 5.4 seconds (10%–24.4%). In addition, the increase in totVarAcc correlated with $\Delta\text{Speed}_{\text{PC2–PC1}}$ and $\text{Time}_{\text{PC3–P2}}$ (Table 1). Also, for INT, there were no significant correlations between improvement in $\text{Speed}_{\text{PC2–PC1}}$, $\text{Time}_{\text{PC3–P2}}$, or total race time with the performance indicators ($V_{\max}$ flat/uphill or VO_2peak skate). However, the skiers that had lower preintervention $\text{Speed}_{\text{PC2–PC1}}$, $\text{Time}_{\text{PC2–PC1}}$, and total race time improved more than the other skiers (Table 1). Individual and mean values for $\text{Speed}_{\text{PC2–PC1}}$ and $\text{Time}_{\text{PC2–PC1}}$ are given in Table S2 in the Supplementary Material (available online).

Overall Performance and Performance in Different Terrain

The intervention group reduced time in S3, S4, S8, S10, and S12 compared with CON (Table 2), and totVarAcc increased more for INT compared with CON in all downhill segments (S3, S6, S8, S10, and S12; all $P < .001$), see Figure 4 and Table 2.

A higher relative improvement in INT versus CON was found in overall downhill (–14.4 s; 95% CI, –21.4 to –7.4 s; $P < .001$) and flat terrain (–6.5 s; 95% CI, −11.0 to −1.9 s; $P = .006$), while no significant differences were found for uphill terrain (–9.3 s; 95% CI, –31.2 to 13.2 s; $P = .426$) or overall race time (–32.2 s; 95% CI, −100.2 to 35.9 s; $P = .339$). No changes in percentage of $\text{HR}_{\max}$ (INT: –0.54% [0.98%] point, $P = .058$; CON: –0.24% [1.41%] point, $P = .561$) or RPE (INT: 0.5 [1.25], $P = .527$; CON: 0.5 [1.75]; $P = .257$) from Race1 to Race2 were observed. Individual and mean values for the time used in the terrain types, total race time, percentage of $\text{HR}_{\max}$, and RPE in Race1 and Race2 are displayed in Figure 3 and Table 2, while details are given in Tables S2 and S3 in the Supplementary Material [available online]. The continuous speed difference (mean lap value) between INT and CON according to the elevation profile and the time difference for each segment are displayed in Figure 5.

Discussion

The present study investigated the effects of video- and sensor-based feedback for implementing a specific micropacing strategy when preparing for an XC skiing competition. The intervention group significantly reduced time spent in the targeted downhill segment, along with shorter time spent overall in downhill and flat terrains, compared with the matched controls. However, no significant effects of the intervention were observed in uphill terrain or for overall race performance.

As expected, INT improved performance significantly more than CON in the specific downhill segment targeted during the

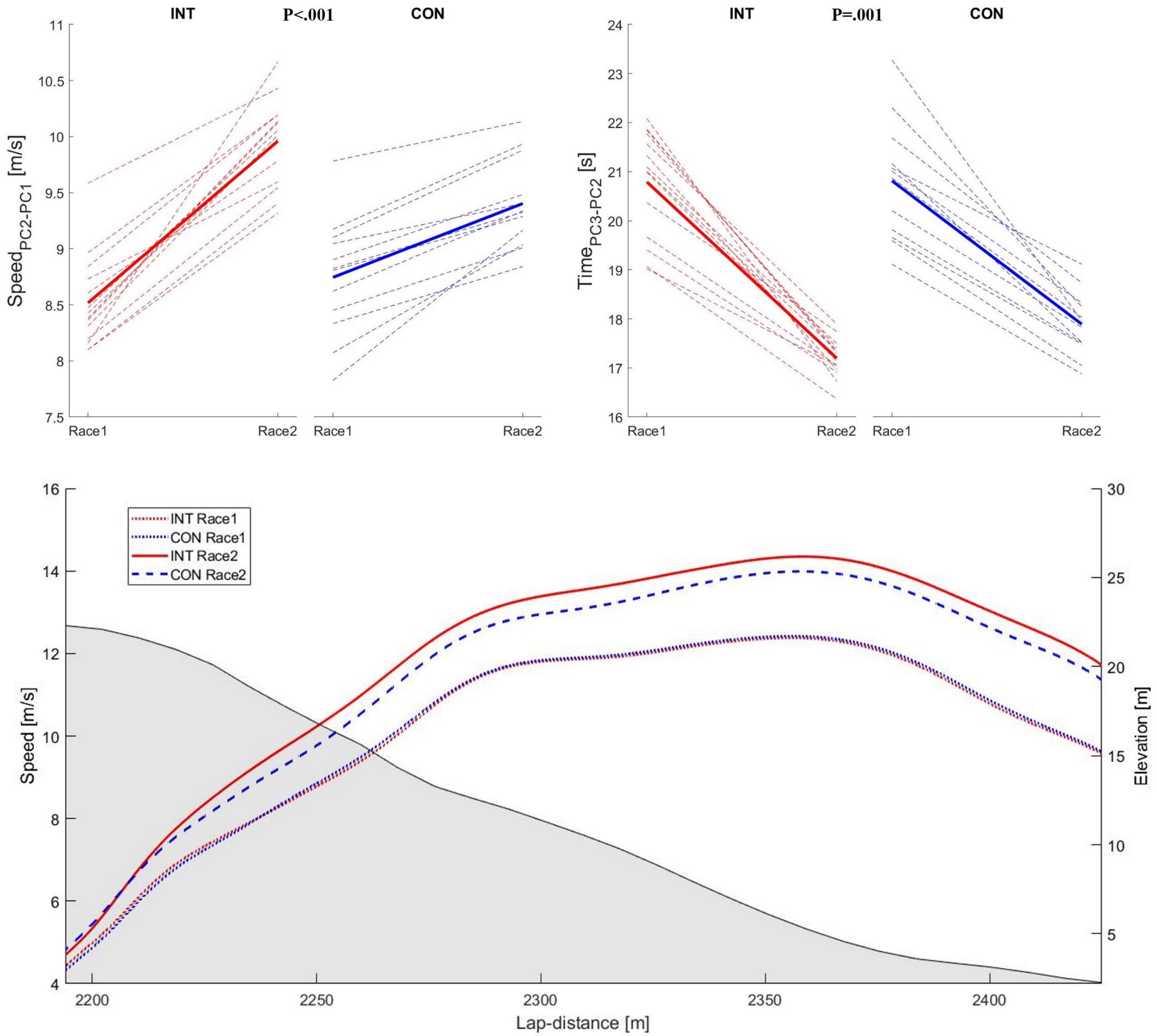

Figure 2 — Downhill segment 10. Upper graphs: Speed$_{PC2-PC1}$ and Time$_{PC2-PC1}$ (s) in Race1 and Race2 for the INT and the CON, individual values printed in dotted lines, and mean values in bold lines. *P* values for relative differences between groups are displayed. Lower graph: Continuous speed ($m \cdot s^{-1}$; measured with GNSS) for Race1 and Race2 for INT and CON. CON indicates control group; INT, intervention; PC, photocell.

micropacing training session. This is likely explained by more active poling and leg kicks (measured by the total variance of the chest acceleration) leading to increased speed and reduced time in the subsequent downhill. This is in line with previous findings during a classical sprint competition, where instant speed during the acceleration phase over hilltops was related to the time spent in the subsequent downhill segment.[12]

The increased speed at the start of the downhill was not linked to the skiers' maximal aerobic power (VO_2peak in skating) or the 20-m speed tests, implying that the increase in performance occurred independently of these factors. However, the skiers with lower initial speed in the specific downhill segment during Race1 improved their speed more than the skiers with higher initial speed. In addition, the skiers with longer race time in Race1 improved overall race time more than faster skiers. Accordingly, individual strengths and weaknesses should likely provide the point of departure for further developing micropacing strategies. This is in line with the recent intervention study by Losnegard,[11] showing that XC skiers with a fast-start pacing pattern improved their performance by reducing the speed in the first uphill. However, there is a lack of studies comparing the costs and benefits of different micropacing strategies in XC skiing or similar endurance sports. More research is therefore required to understand this aspect of racing.

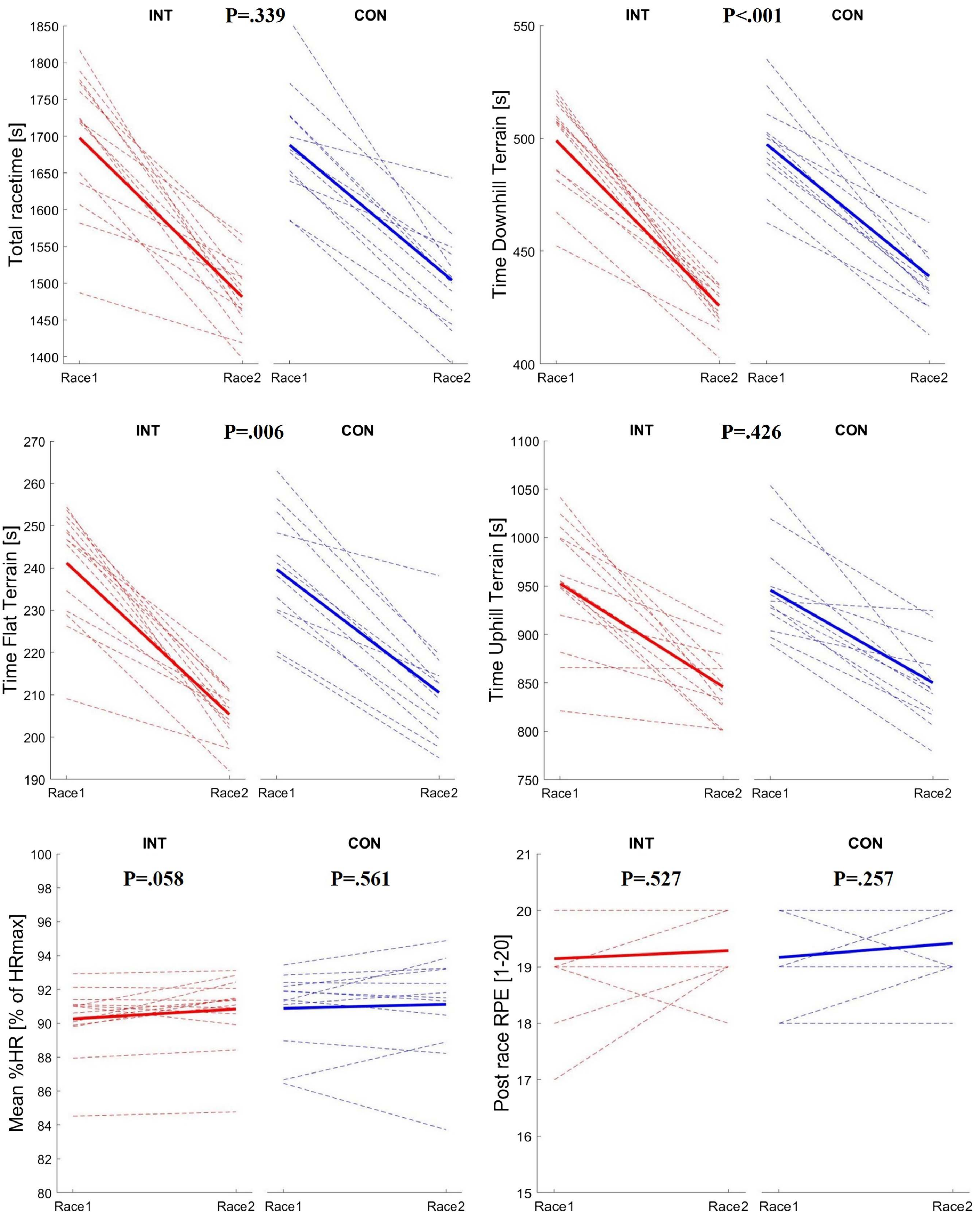

Figure 3 — Individual and mean values for Race1 and Race2 for the INT and the CON for total race time (s); overall time in downhill, flat, and uphill terrain; relative HR in % of maximal HR; and RPE. *P* values for relative improvement in total race time, overall time in downhill, flat and uphill terrain from Race1 to Race2 between groups, and *P* values for change in HR and RPE from Race1 to Race2 for both groups are displayed on the figure. CON indicates control group; HR, heart rate; INT, intervention group; RPE, rating of perceived exertion.

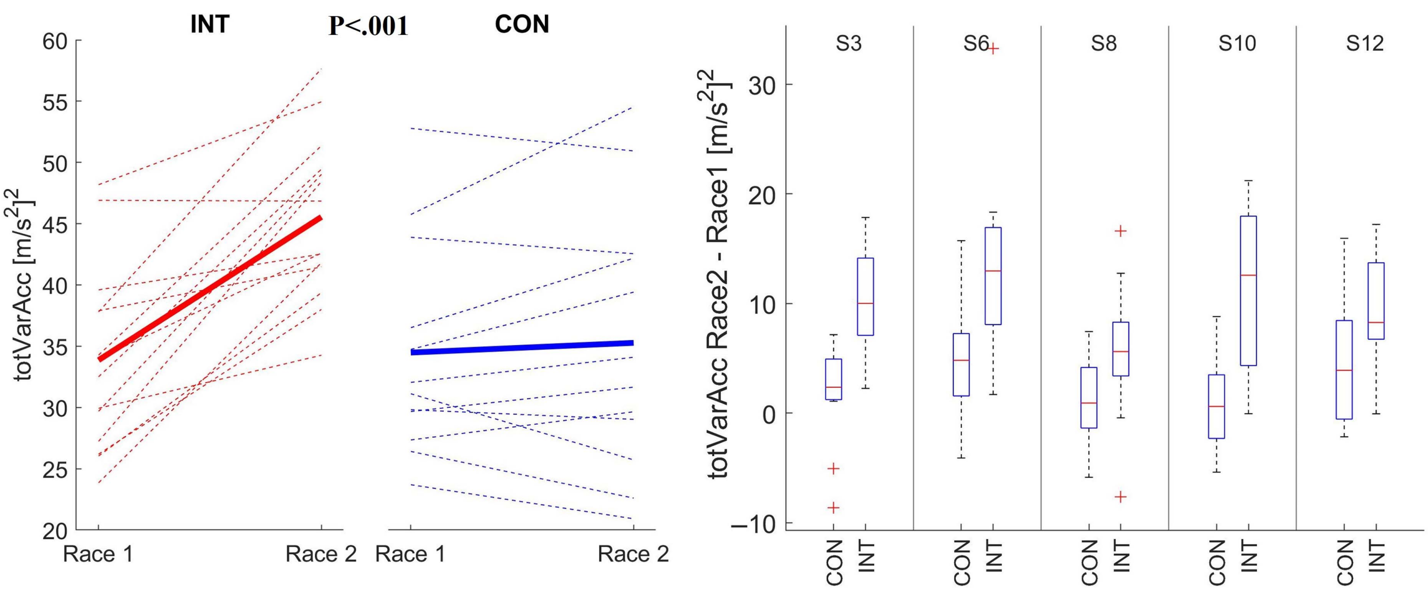

Figure 4 — The totVarAcc ([m·s^{-2}]^2) on the hilltop of S10 for the INT and the CON for Race1 and Race2 (left graph), *P* value for relative difference between groups is displayed. Relative totVarAcc (%) on the hilltops for Race2 compared with Race1 for INT and CON for all downhill segments, observations that lie outside the interval defined by the box and outliers are marked with red crosses. (all $P < .001$) (right graph).

Table 1 Correlations (*R*) Between Improvement From Race1 to Race2 and Performance Indicators for the Intervention Group

	ΔSpeed$_{PC2-PC1}$, m·s^{-1}		ΔTime$_{PC3-PC2}$, s		ΔRaceTime, s		ΔtotVarAcc$_{S10}$, (m·s^{-2})^2	
	R	*P*	*R*	*P*	*R*	*P*	*R*	*P*
VO_2peak skate, mL·kg^{-1}·min^{-1}	.19	.553	–.32	.313	–.32	.319	.03	.902
Max speed flat, m·s^{-1}	.06	.837	.08	.800	.04	.906	.26	.201
Max speed uphill, m·s^{-1}	.08	.796	.13	.664	.16	.576	.01	.980
Race1: Speed$_{PC2-PC1}$, m·s^{-1}	–.57	.035	–.68	.007	–.30	.290	.30	.144
Race1: Time$_{PC3-PC2}$, s	.27	.065	.93	.000	.66	.010	.26	.205
Race1: RaceTime, s	.33	.247	.86	.000	.86	<.001	.35	.082
StartTime, min after 1.start	–.33	.225	–.56	.039	–.65	.012	.22	.251
Intracorrelation								
ΔSpeed$_{PC2-PC1}$, m·s^{-1}	NA	NA	.59	.026	.24	.405	.735	<.000
ΔTime$_{PC3-PC2}$, s	.59	.026	NA	NA	.85	<.001	.50	.009
ΔRaceTime, s	.24	.405	.850	<.001	NA	NA	.54	.004
ΔtotVarAcc$_{S10}$, (m·s^{-2})^2	.75	<.000	.50	.009	.54	.004	NA	NA

Abbreviations: ΔRaceTime, improvement in total race-time from Race1 to Race2; ΔSpeed$_{PC2-PC1}$, increased speed after the acceleration phase in downhill segment 10 from Race1 to Race2; ΔTime$_{PC3-PC2}$, decrease in glide time in downhill segment 10 from Race1 to Race2; ΔtotVarAcc$_{S10}$, (m·s^{-2})^2, increase in total variation of chest acceleration on hilltop from Race1 to Race2; PC, photocell.

Although the skiers received specific feedback and performed practical training only in 2 of the 5 downhill terrain segments, INT improved performance more than CON in 4 downhill segments during the competition. This led to significantly greater improvements in INT versus CON in overall downhill terrain. The lack of improvement in one of the downhills (S6) was likely due to this segment being relatively short and steep, which limits the amount of time possible to save time by employing this micropacing strategy. Overall, this indicates that the employed intervention was sufficient to adopt better micropacing strategies also in other downhills than those focused on during the practical training session.

No effects of the intervention on uphill or overall race performance were found. Since the skiers were instructed to keep the same pace in the uphill sections before and after the intervention, the lack of improvement in uphill sections was not surprising. Previous studies clearly show a higher portion of time spent skiing uphill than downhill and that uphill terrain is the most performance-differentiating terrain in XC skiing.[7–10] A possible explanation for the lack of improvement in overall race performance is that

Table 2 Time (s) in Segments and Overall Flat/Up/Down Terrain per Lap (Mean Value for the 3 Laps and SD for the INT and the CON for Race1 and Race2

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	Lap	Lap	Lap	Lap
Segment	**Flat**	**Up**	**Down**	**Flat**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Up**	**Down**	**Flat**	**Flat**	**Up**	**Down**	**All**
Race1																	
$Time_{INT}$, s	9.5	142.0	27.0	46.5	33.9	18.0	41.9	56.9	48.1	24.5	51.6	40.0	24.5	80.4	317.4	166.3	564.2
$Time_{CON}$, s	9.5	140.9	26.3	45.9	33.5	18.2	41.5	56.5	47.9	24.7	51.4	40.1	24.5	79.9	315.2	165.8	560.9
Std_{INT}, s	0.4	9.8	1.1	2.9	2.2	0.6	3.3	2.5	2.7	0.9	4.0	2.1	1.3	4.3	20.3	6.7	31.3
Std_{CON}, s	0.4	6.3	1.1	2.8	2.5	0.4	3.0	2.5	2.9	1.1	2.2	1.7	1.5	4.4	15.8	6.4	26.6
Race2																	
$Time_{INT}$, s	8.2	131.4	24.8	40.6	29.3	16.7	33.1	48.2	42.9	21.2	45.2	31.0	19.7	68.4	282.0	142.0	492.4
$Time_{CON}$, s	8.3	132.7	25.5	41.4	29.5	17.1	33.6	49.7	42.9	21.9	44.6	32.2	20.4	70.2	283.4	146.3	499.9
Std_{INT}, s	0.2	5.1	0.7	1.7	1.5	0.4	1.7	1.6	1.7	0.5	2.3	0.9	0.6	2.2	11.2	3.3	16.7
Std_{CON}, s	0.4	6.0	1.1	2.2	1.8	0.7	2.1	2.2	2.9	0.7	2.6	1.5	1.3	3.8	14.1	5.4	23.3
Time in segments, s, linear mixed model																	
$\Delta_{INT-CON}$	–0.18	–2.08	–1.25	–1.36	–0.40	–0.29	–0.8	–1.69	–0.14	–0.55	0.50	–1.03	–0.62	–2.15	–3.01	–4.79	–9.97
Upper CI	–0.40	–5.78	–1.75	–2.34	–1.45	–0.59	–1.95	–2.68	–1.52	–0.9	–0.89	–1.84	–1.25	–3.67	–10.41	–7.12	–20.42
Lower CI	0.04	1.62	–0.76	–0.38	0.65	0.00	0.35	–0.70	1.25	–0.19	1.89	–0.22	0.02	–0.63	4.39	–2.47	0.48
P	.111	.271	<001	.006	.458	.053	.173	0.001	.846	.003	.480	.013	0.058	.006	.426	<001	.061
totVarAcc, $(m\cdot s^{-2})^2$, linear mixed model																	
$\Delta_{INT-CON}$			4.89			4.16		3.08		6.18		3.71					
Upper CI			3.43			2.01		1.24		4.48		2.07					
Lower CI			6.36			6.31		4.91		7,88		5.34					
P			<.000			<.000		<.001		<.000		<.000					

Abbreviations: $\Delta_{INT-CON}$, difference in performance for INT compared with CON from Race1 to Race2; CI, confidence interval; CON, control group; INT, intervention group; totVarAcc, total variation of chest acceleration on hilltops. Note: The difference in performance (time in segments or acceleration intensity on hilltops) between INT compared with CON in Race1 to Race2 including *P* values and CIs are from a linear mixed model where skier id is random factor and lap and race day/group are fixed factors.

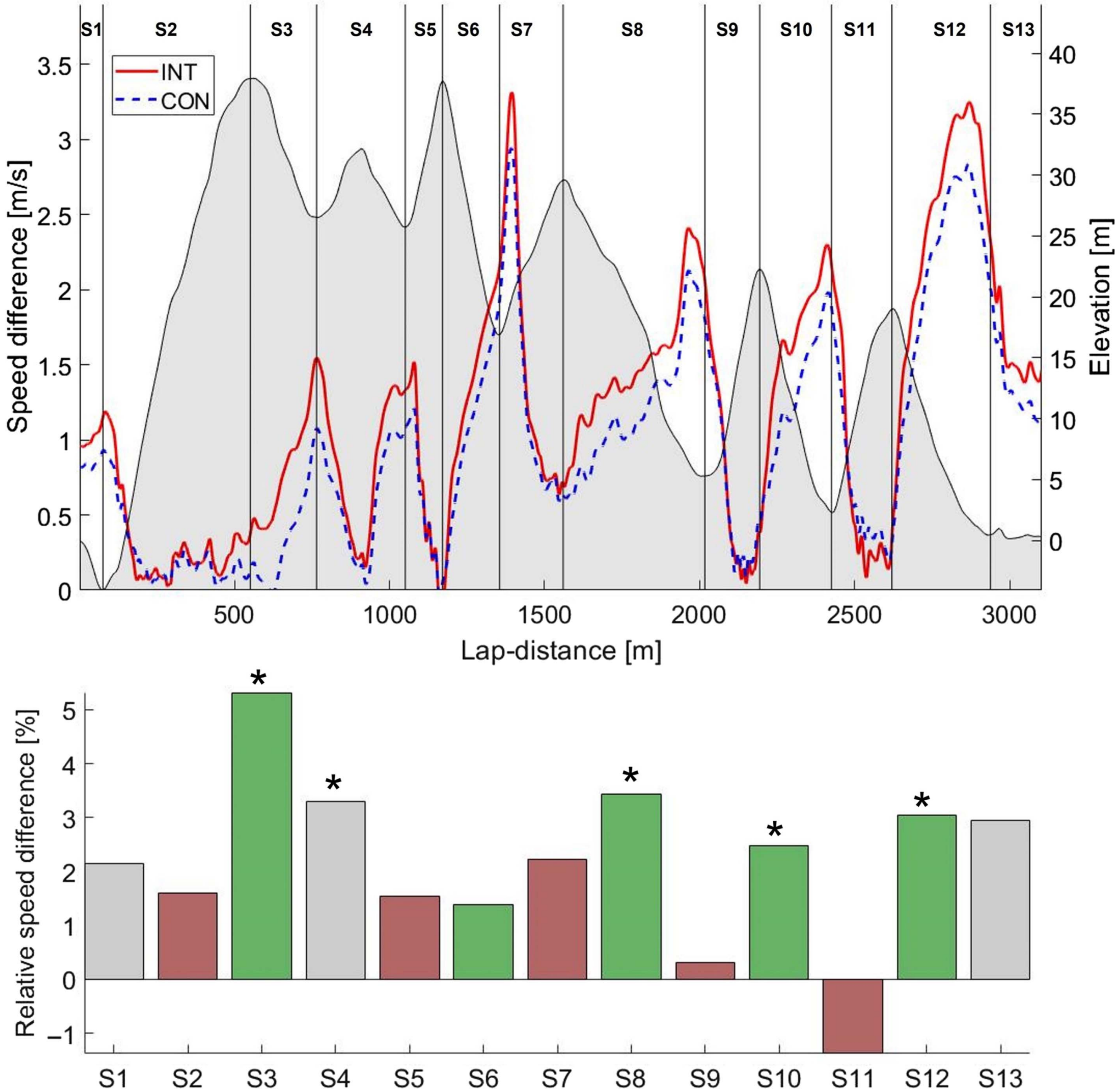

Figure 5 — Upper graph: Mean speed difference ($m \cdot s^{-1}$) and elevation (m) for Race2 compared with Race1 as a function of lap distance (m) for the INT and the CON. Lower graph: Relative improvement in speed for each segment for INT compared with CON in Race2 compared with Race1. *Significant difference in improvement between the groups ($P < .05$). CON indicates control group; INT, intervention group.

the individual performance differences from Race1 to Race2 in the uphill terrain have "masked" the improvements observed in the downhill sections in this relatively heterogeneous group of skiers. This is also supported by a recent investigation of micropacing strategies during a distance XC skiing competition, showing that skiers with shorter race times skied faster in specific parts of the uphills.[23] The lack of improvement in the overall performance could also be that some of the high-level skiers included in our study already were familiar with the micropacing strategy and therefore gained little time from the intervention. Lastly, although the study design (ie, balanced groups both according to performance and starting time) took into account some of the changes in snow and weather conditions, we cannot exclude that the nonlinear changes in the external conditions during the race days may have impacted the results.

Although the observed improvements in downhill terrain in INT did not significantly influence the overall competition performance, better downhill performance might be crucial when the margins between skiers are small.[12,24] In the current study, INT improved 14.6 s/2.9% in downhill and 6.5 s/2.7% in flat terrain compared with CON, corresponding to 1.0% and 0.4% of the total competition time, respectively. This improvement is greater than the smallest worthwhile improvement (defined as the required improvement in performance that could significantly influence the results), calculated to be 0.3% to 0.4%.[24] An interesting question is also whether a more extended intervention period, including several training sessions with feedback in different race courses can improve skiers micropacing strategy enough to influence the overall result in XC skiing.

Practical Applications

High-level XC skiers can reduce the time spent in downhill and flat terrain by implementing a terrain specific micropacing strategy using video- and sensor-based feedback in a time-efficient manner. The combination of a theoretical lecture, including video and speed analysis highlighting the potential to gain seconds, and objective feedback directly after each trial during a training session, seems to have created an effective learning process. Furthermore, this methodology can likely be used to develop better micropacing skills in other parts of the course or by focusing on technical aspects like the choice of subtechnique or regulation of cycle length and rate. Nevertheless, it is important that the coaches and skiers carefully analyze race courses and evaluate where there are the most seconds to gain from such strategies. Furthermore, the time spent training on this must also be weighed against improving other factors of importance for performance in XC skiing (eg, high aerobic power and efficient technique).

Conclusions

Targeted training combined with video- and sensor-based feedback led to a successful implementation of a terrain-specific micropacing strategy in XC skiing, which induced higher speed and reduced the time spent in downhill- and flat terrain sections compared with a control group. However, no change in overall performance was observed between the 2 groups of XC skiers.

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