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Research article

Impact of Incline, Sex and Level of Performance on Kinematics during a Distance Race in Classical Cross-Country Skiing

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Abstract

Here, female and male elite cross-country (XC) skiers were compared on varying terrain during an official 10-km (women) and 15-km (men) Norwegian championship race. On the basis of race performance, 82 skiers were classified as fast (FS) (20 women, 20 men) or slower (SS) (21, 21) skiers. All were video recorded on flat (0°), intermediate (3.5°), uphill (7.1°) and steep uphill (11°) terrain during the race at a distance of 0.8, 1.2, 2.1 and 7.1 km from the start, respectively. All skiers employed exclusively double-poling (DP) on the flat section and, except for the male winner, exclusively diagonal stride (DIA) on the uphill sections. On the intermediate section, more men than women utilized DP and fewer DIA ($p = 0.001$), with no difference in kick double-poling (DPK). More FS than SS utilized DPK and fewer DIA ($p = 0.001$), with similar usage of DP. Males skied with faster and longer cycles but lower cycle rate compared with females ($p < 0.001$), with largest absolute sex differences on flat terrain ($p < 0.001$) and largest relative differences for cycle velocity and length on intermediate and uphill terrain. External power output rose with increasing incline, being higher for men and FS ($p < 0.001$). Cycle velocity on flat terrain was the best predictor of mean race velocity for the men, while cycle velocity on steep uphill was the best predictor for the women (both $p < 0.001$). In conclusion, incline, sex and level of performance influenced cycle characteristics and power output. Greatest absolute sex gap was on flat terrain, whereas the relative difference was greatest on intermediate and steep uphill terrain. We recommend usage of more DP and/or DPK, and less DIA and fewer transitions between techniques on intermediate terrain. Predictors of race performance are sex specific with greatest potential for enhancing performance on flat terrain for men and on steep uphill terrain for women.

Key words: Cycle characteristics; diagonal stride; double poling; kick double poling; power output; video analysis.

Introduction

Classical cross-country (XC) skiing involves as many as five different techniques, in addition to those employed in curves and downhill. During a race, the skier adapts these techniques to the topography, snow conditions (e.g., friction) and skiing speed, taking into consideration his/her individual technical competence and physical capacity (Bergh and Forsberg, 1992; Bilodeau et al., 1992; Norman and Komi, 1987; Nilsson et al., 2004; Smith, 1992). Accordingly, the technique employed by different skiers on any given section of a course may differ extensively.

In the case of classical XC skiing, diagonal stride (DIA) and double poling (DP) are the techniques most often utilized on steep uphill and flat terrain, respectively, with kick double-poling (DPK) often being employed on moderate uphill terrain (Göpfert et al., 2013; Pellegrini et al., 2013). DIA is characterized by alternate poling thrusts synchronized with a kick by the opposite leg. DP is performed without kicking, so that all propulsion is generated via the upper body through the poles. DPK involves a DP motion followed by a kick involving one leg, with the kicking leg typically alternating from cycle to cycle.

During the past three decades, DP has become more and more extensively utilized and today its successful usage determines the outcome of classical XC races (Holmberg et al., 2005; Sandbakk and Holmberg, 2014; Stöggl and Holmberg, 2011; Welde et al., 2017). This gradual shift to DP is probably a response to better preparation/grooming of ski courses along with marked improvement in equipment (e.g. grip/strap, basket/tip of the pole, as well as gliding properties of the skis). This, in turn, has allowed skiers to perform more specific upper body training, since DP can now be utilized more extensively. Accordingly, XC skiers have increased their upper-body strength and endurance and thereby substantially improved their technique (Holmberg, 2015; Stöggl and Holmberg, 2011).

The pronounced increase in racing speed during recent decades (Sandbakk and Holmberg, 2014; Stöggl et al., 2008), along with the more extensive use of DP (Hebert-Losier et al., 2017; Stöggl and Holmberg, 2016; Stöggl and Holmberg, 2011), motivate more detailed examination of cycle characteristics and the utilization of the major techniques by elite skiers on different sections of classical XC distance races involving various types of terrain. Pellegrini and co-workers (2013) have demonstrated that when roller skiing on a treadmill, DP is the preferred technique at low inclines (up to 2°). At moderate inclines (2-3°), their skiers switched to DPK and all employed DIA on inclines greater than 6°. In that investigation, no skiers employed DP on an incline steeper than 4°, while at a fixed incline of 2° DIA could only be used at speeds of 6-14 km/h. These research-

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ers described hypothetical thresholds for transitions between techniques based on pole forces (when 5.5 N/kg was reached, the skiers switched to another technique) and leg thrust time (when this time became less than 0.11 s, this leg action was no longer sustainable).

Furthermore, Stöggl and co-workers (2007) have demonstrated that during a simulated XC sprint race with roller skis on a treadmill, the faster skiers employ longer and fewer total cycles and tend to utilize DP and DPK more extensively. Recently it was demonstrated that elite male skiers use DP and DPK to a greater extent during the first half of a XC skiing distance race, while they switch to DPK during the second half while the slower skiers do the opposite (Welde et al., 2017).

On XC race courses, more than 50% of the total time is spent skiing uphill and uphill performance is thus considered to be the major determinant of success (Bergh and Forsberg, 1992; Bilodeau et al., 1996; Bolger et al., 2015; Mognoni et al., 2001; Norman and Komi, 1987; Sandbakk et al., 2011; 2016). Although a number of biomechanical analyses of XC sprint events have been published recently (e.g. Andersson et al., 2010; Stöggl et al., 2007; Zory et al., 2006), all such analyses performed during actual distance races date back to the 1980-90's (Bilodeau et al., 1996; Norman and Komi, 1987; Norman et al., 1989; Smith et al., 1996). One consistent finding has been that better overall racing performance is associated with greater cycle length and faster cycle velocity on flat (Bilodeau et al., 1996; Norman and Komi, 1987; Smith et al., 1996) and uphill terrain (Bilodeau et al., 1996; Norman and Komi, 1987), where the cycle rate of faster skiers is either lower than (Norman and Komi, 1987) or similar to that of slower skiers (Bilodeau et al., 1996; Smith et al., 1996).

These earlier studies involved either male or female skiers, with no direct sex comparisons. In this context, Sandbakk and colleagues (2014) found that sex differences were more pronounced while using the DP technique. Moreover, Hegge and co-workers (2016) underlined the observation that larger differences in power output between men and women emerge when a greater contribution from the upper body is required. Consequently, the largest sex differences during a XC competition are expected to be observed in connection with sections of the course where DP is the predominant technique employed.

The current study is part of a larger project in which the effects of fatigue (Welde et al., 2017), track topography and sex differences on kinematic variables during a real XC skiing distance competition are being analyzed in detail. The aim of this current study was to compare the techniques employed on various inclines by world- (faster skiers: FS) and national-class (slower skiers: SS) male and female XC skiers during a distance race to their cycle characteristics and performance. Our hypotheses were that 1) longer and faster cycles, but no difference in cycle rate are associated with better performance; 2) performance uphill is more closely related to race outcome than performance on the flat and intermediate sections; 3) the most pronounced sex differences occur on flat and intermediate terrain, especially while using the DP technique, when the contribution from the upper body increases; and 4) faster skiers utilize the DP technique to a greater extent.

Methods

This study was conducted in connection with the 10-km and 15-km classical XC races for women and men, respectively, at the Norwegian National Championships held in Tromsø, in 2016. The study was pre-approved by the *NSD Data Protection Official for Research* in Norway and the subjects fully informed about its nature before providing their consent for us to use their data.

The race course was composed of two 5-km tracks (track A and track B). The men skied track A twice and track B once (A-B-A), for a total racing distance of 15 km, while the women skied track A and B once each (A-B), for a total racing distance of 10 km. The two tracks involved approximately equal distances on uphill, flat and downhill terrain, as well as total climbs of 149 and 185 m, maximal changes in elevation of 72 and 76 m, and maximal climbs of 42 and 38 m, respectively. The competitors were video recorded on four different types of terrain: flat (mean incline -0.3°, range within the site: -0.4 to 1.4°), intermediate (mean 3.5°, range 2-5°), uphill (mean 7.1°, range 6.4-7.9°) and steep uphill (mean 11°, range 9-13°) at distances of 0.8, 1.2, 2.1 and 7.1 km from the start, respectively.

A grooming machine prepared the course on the evening prior to testing and the weather conditions during the race were stable (no wind, air temperature +1° C, snow temperature 0° C, relative humidity 86%), with no problems choosing the optimal wax (base and violet klister for grip, high-fluor paraffin wax combined with fluor powder for glide).

Participants and data analysis

Following the race, 82 of the 202 participants (140 men, 62 women) were classified on the basis of their finishing times as faster skiers (FS: the top-placed 20 women and 20 men) or slower skiers (SS). To obtain relatively homogenous slower groups, the very slowest (i.e., starting with the skier who finished 0.5% (males) or 1.0% (females) slower than the skier who finished immediately before him/her) were excluded to leave 21 men and 21 women as SS. The FS (including four who ranked among the top 10 in the World Cup in 2016 and four medalists at World Championship or Olympic Games) all had finishing times within 8% (men) or 11% (women) of the winner's, whereas the SS skiers were 10-16% (men) and 14-22% (women) slower than the winners.

The cycle characteristics of the skiers on the four different sections were determined with the Kinovea 8.25 software and the total racing time (performance) for each provided by the official timing system (SIWIDATA, Merano, Italy).

Video cameras (Sony HDR-PJ810E, Sony corp., Tokyo, Japan) set at 50 Hz with a shutter speed of 1/500 s recorded the skiers at high resolution (1920 x 1080 progressive scan). Each camcorder was positioned perpendicular to the track 1 m above the ground on top of tripods placed on custom-made wooden platforms, leveled with an electronic inclinometer, and recorded the skiers in a sagittal plane from a distance of 12 - 25 m. The ski tracks were centered in the field of vision and the focus and zoom set to cover at least three cycles of movement per section filmed. The flat and intermediate sections were both 22 m and the two uphill sections 12 m in length.

For purposes of calibration, four red poles were placed on the video-taped sections of the track prior to the race, two at the beginning and two at the end, creating a regular rectangle enclosing the section on both sides (Fig. 1). A fifth pole was set exactly in the middle of the side of this rectangle closest to the camera. The distances between each pair of poles were determined with a measuring tape. In addition, to improve visualization for calibration of the two single tracks and video analysis, two lines were drawn on the snow between the poles, perpendicular to the ski track, using orange fluorescent spray paint. Scaling factors (real-life size to video size) for calibration of the measurements were applied separately to each track by the Kinovea software. None of the skiers changed track within a video-recording site.

Definitions of skiing characteristics and determination of kinematic parameters

The classical skiing techniques were categorized as DIA, DPK and DP. None of the skiers used the herringbone technique during the race. One cycle of movement was defined as lasting from initial contact of the left pole with the ground to the next ground contact with this same pole. Cycle length and time were determined as the distance or the time, respectively, between these two ground contacts and the velocity of every cycle obtained by dividing cycle length by cycle time. Poling time was the period from the left pole contact with the ground to termination of this contact and pole recovery/swing time as the period when the tip of the pole was in the air (Figure 1). The values for each parameter during at least three full cycles (excluding transitions from one technique to another) were averaged for further analysis, irrespective of the technique applied (e.g., even when different techniques were used on the intermediate section).

External power calculations

Propulsive external power was calculated as the sum of the power exerted against gravity, friction and air resistance (Swarén and Eriksson, 2016) (i.e., neglecting accelerations of the center of mass and of body segments with respect to this center of mass (internal work) during the cycle), as follows:

$$P_{prop} = m \cdot g \cdot \sin(\alpha) \cdot v + m \cdot g \cdot \cos(\alpha) \cdot \mu \cdot v + 0.5 \cdot \rho \cdot A' \cdot v^3$$

where m is the mass of the skier (equipment and the body weight provided by each skier), g 9.81 m/s^2, α the angle of incline, v the skier's mean cycle velocity, μ the coefficient of friction (set to 0.03 for all calculations) and A' the drag area (= $C_d \cdot A$ and set to 0.45 m^2, since only propulsive external power while skiing in the upright position was considered) (Leirdal et al., 2006). It was not necessary to take wind speed into consideration, since there was no wind during the race. The density of air (at a temperature of approximately 0°) was set to 1.292 kg/m^3.

Statistical analysis

All data were normally distributed (as assessed by the Shapiro-Wilk test) and are presented as means ± SD (standard deviation), unless otherwise stated. A three-way (4 inclines, 2 sexes and 2 levels of performance) repeated-measures ANOVA, with all main effects and their two-way interactions included, was conducted for each parameter. When this indicated statistical significance, it was followed-up with univariate ANOVA testing to identify the pair-wise differences exactly (i.e., on which of the four inclines). In cases where only two means were compared (i.e., sex and performance level on a given incline), independent-samples t-tests were performed. For these comparisons, the values for women and SS were set at 100%. On the intermediate section (Section 2) gear distribution and its relationship to sex and level of performance were analyzed using cross-tables and the Lambda correlation ($\lambda_{symmetric}$). To determine the relationships between race performance (V_{RACE}) on the four sections and cycle characteristics, stepwise multiple regressions were calculated separately for the women and men. For all analyses, the level of statistical significance was set at $\alpha = 0.05$. All statistical analyses were carried out utilizing the SPSS 24.0 (SPSS Inc, Chicago, IL, USA) and Office Excel 2010 (Microsoft Corporation, Redmond, WA, USA) software.

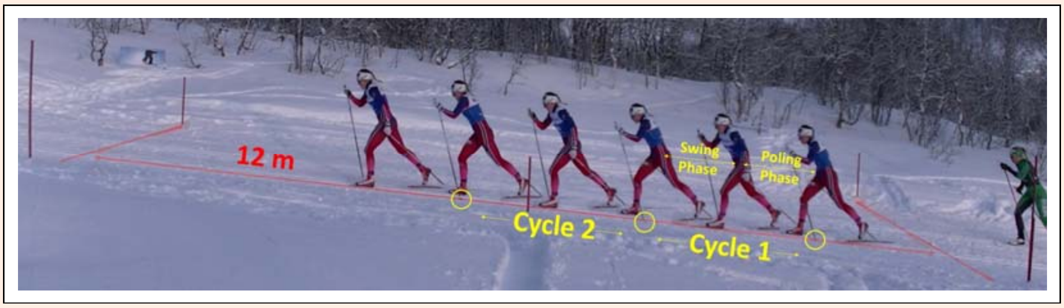

Figure 1. **The set-up of the camera on the sections video-taped, with the four red poles creating a regular rectangle, the fifth pole set exactly in the middle of the side of this rectangle closest to the camera, and two orange lines on the snow between the poles perpendicular to the ski track. In addition, the definitions of the entire cycle (left pole plant to consecutive left pole plant) and poling and swing phases are indicated. The red arrow illustrates the calibration line for determination of the scaling factors (real-life size to video size) for calculations of distance for one of the tracks.**

Table 1. The classical XC techniques employed on the intermediate section (3.5° incline) by faster (FS) and slower (SS) male and female skiers.

Technique(s)	Sex: Women (n=41)	Sex: Men (n=41)	Level of performance: FS (n=40)	Level of performance: SS (n=42)	The individual groups: Women FS (n=20)	Women SS (n=21)	Men FS (n=20)	Men SS (n=21)	Total (n=82)
DP	3	20	12	11	0	3	12	8	23
DPK	11	13	18	6	11	0	7	6	24
DIA	20	1	5	16	5	15	0	1	21
DP & DIA	1	1	1	1	1	0	0	1	2
DP & DPK	0	6	1	5	0	0	1	5	6
DPK & DIA	6	0	3	3	3	3	0	0	6
Total	41	41	40	42	20	21	20	21	82

DP, double poling; DIA, diagonal stride; DPK, double poling with a kick. The values shown are the numbers of skiers utilizing each technique or a combination of techniques.

Table 2. Cycle and pole characteristics of and external power output by the faster (FS) and slower (SS) male (M, n = 41) and female (F, n = 41) skiers on the different inclines during a classical XC race and their interactions with sex and level of performance.

Parameter		Flat (0°)		Intermediate (3.5°)		Uphill (7.1°)		Steep uphill (11°)		ANOVA		
		F	M	F	M	F	M	F	M	Incline	Incline x Sex	Incline x PERF
Cycle velocity (m/s)	Total	6.77 (.60)*$^{S P}$		4.51 (.53)*$^{S P}$		3.23 (.37)*$^{S P}$		2.23 (.37)*$^{S P}$		$F_{3,72}=3869$ p<0.001	$F_{3,72}=26$ p<0.001	NS
	FS	6.30 (.23)	7.42 (.18)	4.26 (.20)	5.13 (.21)	3.09 (.17)	3.66 (.16)	2.23 (.25)	2.66 (.29)			
	SS	6.03 (.35)	6.86 (.32)	3.82 (.31)	4.63 (.23)	2.73 (.16)	3.31 (.18)	1.89 (.14)	2.09 (.26)			
Cycle rate (Hz)	Total	.96 (.08)*^{S}		.91 (.10)*		1.01 (.08)*^{S}		1.12 (.07)*$^{S P}$		$F_{3,72}=168$ p<0.001	NS	NS
	FS	1.00 (.09)	.93 (.05)	.92 (.10)	.92 (.11)	1.06 (.09)	.99 (.08)	1.18 (.07)	1.10 (.06)			
	SS	.97 (.09)	.92 (.04)	.90 (.07)	.90 (.10)	1.03 (.07)	.97 (.04)	1.12 (.04)	1.09 (.05)			
Cycle length (m)	Total	7.05 (.92)*^{S}		4.96 (.73)*$^{S P}$		3.20 (.46)*$^{S P}$		1.99 (.35)*$^{S P}$		$F_{3,72}=2683$ p<0.001	$F_{3,72}=33$ p<0.001	NS
	FS	6.33 (.62)	8.00 (.48)	4.66 (.48)	5.63 (.60)	2.92 (.21)	3.72 (.27)	1.89 (.19)	2.41 (.31)			
	SS	6.25 (.62)	7.46 (.48)	4.24 (.33)	5.21 (.59)	2.68 (.25)	3.40 (.21)	1.69 (.13)	1.93 (.25)			
Absolute poling time (s)	Total	.27 (.02)*^{P}		.42 (.06)*^{S}		.47 (.03)†^{P}		.47 (.04)†^{P}		$F_{3,72}=1090$ p<0.001	$F_{3,72}=2.7$ p=0.051	$F_{3,72}=5.3$ p=0.002
	FS	.27 (.01)	.27 (.02)	.44 (.09)	.39 (.04)	.45 (.03)	.45 (.03)	.44 (.04)	.46 (.04)			
	SS	.29 (.02)	.28 (.02)	.44 (.03)	.41 (.03)	.49 (.04)	.47 (.02)	.51 (.03)	.48 (.03)			
Absolute pole swing time (s)	Total	.78 (.08)*^{S}		.71 (.11)*		.53 (.06)*^{S}		.42 (.04)*^{S}		$F_{3,72}=656$ p<0.001	NS	NS
	FS	.74 (.09)	.82 (.06)	.69 (.14)	.73 (.11)	.51 (.06)	.57 (.07)	.40 (.03)	.45 (.04)			
	SS	.75 (.08)	.82 (.05)	.70 (.08)	.73 (.11)	.49 (.06)	.56 (.04)	.39 (.03)	.44 (.04)			
Relative pole swing time (%)	Total	74.0 (2.4)*$^{S P}$		63.0 (5.4)*^{S}		53.3 (3.3)*$^{S P}$		47.1 (3.7)*$^{S P}$		$F_{3,72}=1776$ p<0.001	NS	$F_{3,72}=3.6$ p=0.018
	FS	73.1 (2.4)	75.4 (1.7)	61.0 (8.8)	65.4 (2.6)	53.0 (2.3)	55.5 (3.2)	47.4 (3.3)	49.5 (3.2)			
	SS	72.3 (2.9)	75.0 (1.3)	61.4 (3.0)	64.1 (3.1)	49.7 (2.5)	54.3 (2.4)	43.2 (3.0)	47.8 (2.4)			
External power output (W)	Total	230 (50)*$^{S P}$		310 (77)*$^{S P}$		329 (74)*$^{S P}$		387 (100)*$^{S P}$		$F_{3,72}=440$ p<0.001	$F_{3,72}=23$ p<0.001	$F_{3,72}=10.2$ p<0.001
	FS	189 (17)	292 (14)	251 (25)	400 (39)	275 (29)	415 (26)	324 (50)	515 (44)			
	SS	181 (23)	253 (24)	231 (32)	349 (30)	251 (32)	366 (35)	283 (38)	409 (38)			

Total: all FS and SS men and women combined; All values presented are means (±SD). NS = not significant, PERF = Performance
* significantly different from all other inclines; † significantly different from 0° and 3.5°; ^{S} significant differences between women and men on the same incline; ^{P} significant differences between FS and SS on the same incline

Results

Finishing times

The winner of the men's 15-km race finished in 37 min 47.9 s, 52.6 s ahead of the skier in second place. The fastest female skier had a 10-km finishing time of 28 min 24.5 s (55.7 s ahead of second place). The female and male FS skied on the average 9.3% and 6.7% faster than the corresponding SS ($p < 0.001$). The maximal skiing speeds for the fastest individual female and male skier were, respectively, 6.81 and 7.70 m/s on flat (88.4%), 4.76 and 5.53 m/s on intermediate (86.1%), 3.40 and 3.94 m/s on uphill (86.3%), and 2.94 and 3.06 m/s on steep uphill terrain (96.1%). It should be noted here that the fastest male skier exclusively used the DP technique with no grip wax.

Technique usage on the different sections

During the race, all skiers (of both sexes) employed exclusively the DP technique on the flat section and, except for the male winner, exclusively DIA on the uphill and steep uphill sections. On the intermediate section, the technique employed varied considerably, with 28.0%, 25.6% and 29.3% of the skiers utilizing exclusively DP, DIA and DPK, respectively; 2.4% using both DP and DIA; 7.3% combining DP and DPK; and 7.3% utilizing both DPK and DIA (Table 1).

On the intermediate section, more men (20) than women (3) performed DP, fewer DIA (1 versus 20) and about the same number DPK (13 vs. 11) ($\lambda_{symmetric} = 0.41$, P = 0.001). Furthermore, more FS (18) than SS (6) utilized DPK, fewer DIA (5 versus 16) and about the same number DP (12 vs. 11) ($\lambda_{symmetric} = 0.24$, p = 0.011). Moreover, the women performed more transitions than the men (1.27 ± 0.13 versus 0.44 ± 0.13; $p < 0.001$), independent of the level of performance (p = 0.30).

Effects of sex, incline and level of performance on cycle characteristics

The cycle characteristics for the skiers (total group, women versus men, FS versus SS) on the four different inclines with respect to sex and level of performance are shown in Tables 2 and 3, respectively.

Table 3. **Cycle and pole characteristics of and external power output by faster (FS, n = 40) and slower (SS, n = 42) male (M, n= 41) and female (F, n =41) skiers during a classical XC race with respect to sex and level of performance.**

	Sex		Level of performance		ANOVA		
Parameter	**F**	**M**	**FS**	**SS**	**Sex**	**Level of performance**	**Sex x Level of performance**
Cycle velocity (m/s)	3.91 (.02)	4.63 (.02)	4.49 (.02)	4.07 (.02)	P<0.001	P<0.001	P=0.024
Cycle rate (Hz)	1.02 (.01)	.98 (.01)	1.01 (.01)	.99 (.01)	P<0.001	P=0.015	NS
Cycle length (m)	3.83 (.04)	4.72 (.04)	4.45 (.04)	4.11 (.04)	P<0.001	P<0.001	P=0.066
Absolute poling time (s)	.42 (.00)	.40 (.00)	.40 (.00)	.42 (.00)	P=0.007	P<0.001	NS
Absolute pole swing time (s)	.58 (.01)	.64 (.01)	.61 (.01)	.61 (.01)	P<0.001	NS	NS
Relative pole swing time (%)	57.6 (.3)	60.9 (.3)	60.0 (.3)	58.5 (.3)	P<0.001	P=0.001	NS
External power output (W)	248 (4)	375 (4)	333 (4)	291 (5)	P<0.001	P<0.001	P=0.003

All values presented are means (± SE) of the pooled values for all four sections (i.e., inclines for -0.3°, 3.5°, 7.1°, 11°). NS = not significant.

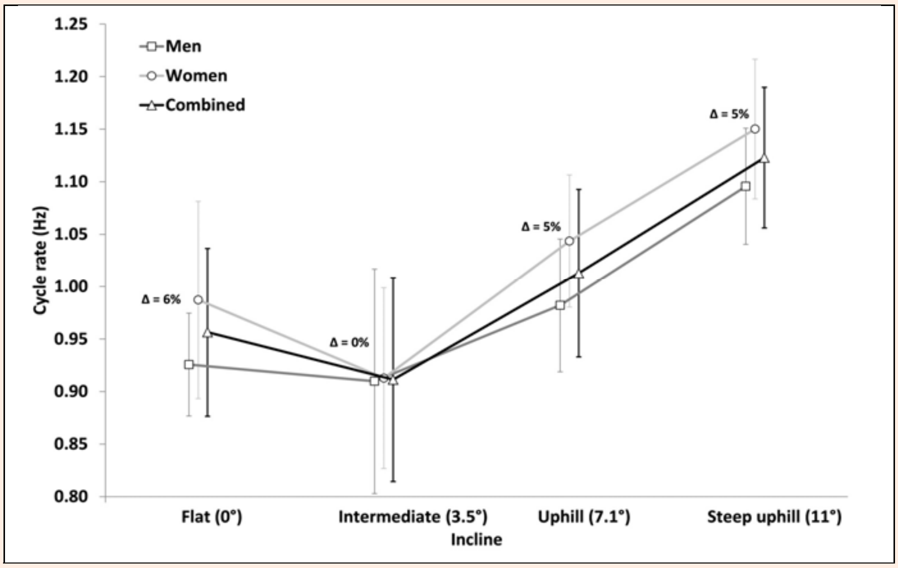

Figure 2. **Cycle rate (means ± SD) employed by our elite male (n = 41) and/or female (n = 41) skiers on flat, intermediate, uphill and steep uphill terrain during the 15- and 10-km XC distance races, respectively, at the Norwegian Championships in 2016.** The percentage differences (Δ) are relative to the mean value for the women designated as 100%.

The steepest uphill terrain was associated with a 67% lower cycle velocity, 17% higher cycle rate, 72% shorter cycles, 74% longer poling time, 46% and 36% shorter absolute and relative pole swing times, respectively, and 67% more external power output than the flat section (all $p < 0.001$). In the case of cycle rate a J-shaped pattern was observed, with the lowest values on intermediate and highest on steep uphill terrain (Figure 2).

In comparison to the male skiers, the women demonstrated on average (i.e., for all inclines combined) a 15.6% slower cycle velocity, 4.1% faster cycle rate, 18.9% shorter cycles, 9.3% shorter swing time, 5.0% longer poling time and 34% lower external power output (all $p < 0.01$). The differences between SS and FS were similar to those between men and women (all $p < 0.02$), with the exceptions of a 2% lower SS cycle rate ($p = 0.02$) and no difference in absolute swing time.

There was an interaction between sex and incline ($p < 0.001$) with respect to cycle velocity and cycle length (Figure 3), with more pronounced absolute sex differences on the flat and intermediate terrain than on the two steeper uphill sections. In contrast, the absolute sex difference in external power output became more pronounced with increasing incline ($p < 0.001$) which was not, however, the case for the relative sex differences (%). Similarly, the interaction between level of performance and incline ($p < 0.001$) exhibited both greater absolute and relative differences in external power output on the steeper than flatter terrain. Finally, the steeper the incline, the longer the absolute and relative poling times and the shorter the relative pole swing time of the SS compared to the FS (interaction incline x level of performance: $p = 0.002$ and $p = 0.018$, respectively).

Characteristics of first three finishers

In comparison to the remaining skiers (38 female and 38 male skiers), the female and male medalists demonstrated the following distinct differences: 1) While there was no clear difference in the body weight for the male skiers (75.7 kg for the medalists versus 78.0 kg) the female medalists weighed approximately 5 kg more (67.7 kg vs. 62.6 kg). 2) On all sections external power output by the female medalists was clearly higher, which was not the case for the men. 3) For both sexes and on all sections, the medalists exhibited clearly higher cycle velocities and longer cycles. 4) While there was no obvious difference in cycle rate for the women, the best three male skiers demonstrated a higher cycle rate on the steep (1.05 vs. 0.98 Hz) and very steep (1.15 vs. 1.09 Hz) uphill terrain.

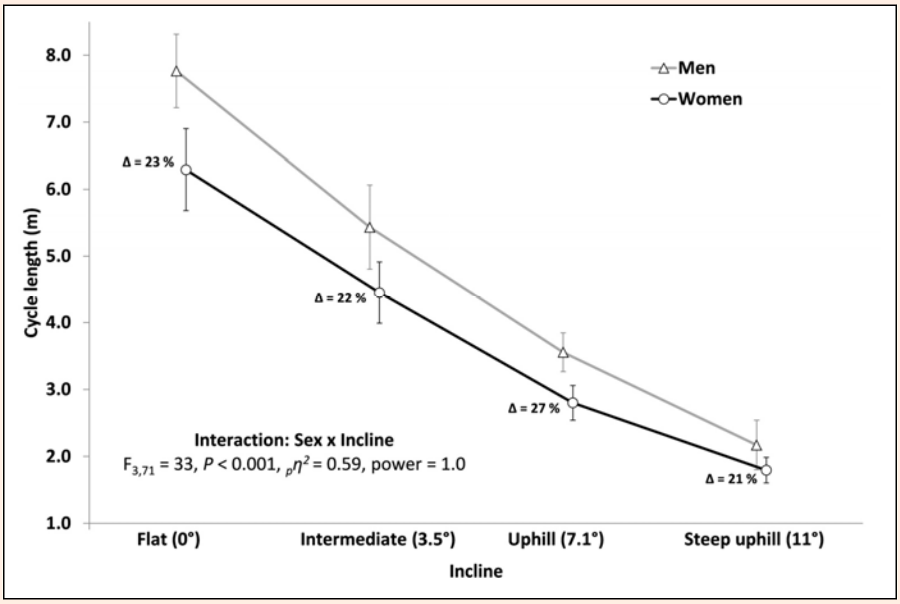

Figure 3. Cycle lengths (means ± SD) employed by our elite male (n = 41) and female (n = 41) skiers on flat, intermediate, uphill and steep uphill terrain during the 15- and 10-km XC distance races, respectively, at the Norwegian Championships in 2016. There was a significant interaction between sex and incline with respect to cycle length and cycle velocity, with more pronounced absolute sex differences on the flat and intermediate inclines than the two steeper uphill sections ($p < 0.001$). The percentage differences (Δ) are relative to the mean value for the women, designated as 100%.

Determinants of overall performance

Multiple stepwise regression analysis revealed the following parametric predictions of race performance (V_{Race}, mean velocity) ordered according to decreasing Beta values by the female and male skiers:

Women:

V_{Race} (m/s) = 0.684 · [velocity on steep uphill terrain (m/s)] + 0.448 · [velocity on intermediate terrain (m/s)] + 1.482. ($R^2 = 0.91$; adjusted $R^2 = 0.83$; $P < 0.001$, SEE = 0.13).

Men:

V_{Race} (m/s) = 0.271 · [velocity on flat terrain (m/s)] + 0.237 · [velocity on steep uphill terrain (m/s)] + 0.301 · [velocity on uphill terrain (m/s)] + 2.499. ($R^2 = 0.91$; adjusted $R^2 = 0.83$; $P < 0.001$; SEE = 0.11).

In addition to cycle velocity, which was a predictor in all situations, cycle length on the intermediate ($r = 0.46$, $p = 0.002$), uphill ($r = 0.51$, $p = 0.001$) and steep uphill ($r = 0.61$, $P < 0.001$) terrain and on the flat ($r = 0.45$, $p = 0.003$), uphill ($r = 0.55$, $p < 0.001$) and steep uphill ($r = 0.61$, $p < 0.001$) terrain was related to V_{Race} for the women and men, respectively. Cycle rate was only related to V_{Race} for the female skiers on the steep uphill section ($r = 0.50$, $p = 0.001$).

Discussion

The major findings of the present investigation are as follows: 1) As the incline increased, cycle velocity, cycle length and pole swing time were reduced, while poling time and external power output rose. A J-shaped pattern with respect to cycle rate was observed, with the lowest values on intermediate and highest on steep uphill terrain. 2) There was a main effect for sex and level of performance, with longer and more rapid cycles for the men compared with women and for FS compared with SS. The largest absolute sex differences in cycle velocity and cycle length were observed on flat terrain. 3) On the intermediate incline the men employed DP and DPK to a greater extent than the women, with the women utilizing primarily DPK and DIA and performing more transitions. The FS employed DPK to a greater and DIA to a lesser extent than the SS, with approximately equal usage of DP. 4) For both sexes and on all sections the three fastest skiers exhibited clearly higher cycle velocities and longer cycles than the other skiers. 5) Superior race performance was correlated primarily to higher cycle velocity on steep uphill and intermediate terrain for the women and to higher cycle velocity on flat, steep uphill and uphill terrain for the men. In addition to more rapid cycles, longer cycles were associated with superior race performance by both the male and female skiers, whereas a high cycle rate improved performance only for the women on the steep uphill section.

The influence of incline on cycle characteristics and external power output

An increase in incline affected all of the cycle characteristics monitored, with reductions in cycle velocity, cycle length and pole swing time (both absolute and relative to cycle time) and enhancement of poling time and external power output. With the exception that poling time was independent of incline in their case, these findings are consistent with those of Pellegrini and colleagues (2011) on the effects of incline (2 – 8°) during DIA treadmill roller skiing at a fixed speed of 9 km/h.

To the best of our knowledge, this is the first report on external power output on various inclines during a XC distance race on snow. Here, the external power output was highest on the steepest incline, where the mean of 356 W (range 213 - 520 W) was comparable to values observed in connection with a simulated classical XC sprint race by elite XC skiers roller skiing on a treadmill (range 240 - 445 W) (Andersson et al., 2010), but approximately 40% higher than those reported by Pellegrini and co-workers (2011) for female elite skiers using DIA on a treadmill (253 W at 8° and 2.5 m/s). The fact that our values are higher than those reported by Pellegrini and co-workers (2011) might be due to the higher incline of our steepest terrain (11° versus 8°); the greater average mass of our skiers (63 kg for the women and 78 kg for the men here versus 54 kg for the women in Pellegrini's study); our faster skiing speeds on the 7.1° incline (3.23 versus 2.5 m/s), with almost similar skiing speeds on the very steep incline (2.23 versus 2.5 m/s), and the effect of air resistance when skiing on-snow. Our results also compare well to the mean external power output (300 – 400 W) reported by Swarén and Eriksson (2016) during a classical XC sprint race for elite male and female skiers.

In contrast to the linear changes in cycle velocity and cycle length with increasing incline, cycle rate demonstrated a J-shaped pattern, with the lowest rate on the intermediate terrain and the highest on the steep uphill section (Figure 2). This differs from the findings of Pellegrini and colleagues (2011) that at a constant DIA speed of 9 km/h, cycle time declined as the incline rose from 2° to 8°. This discrepancy might reflect the free choice of techniques by our skiers, which resulted in variations in the technique employed on the intermediate incline (see also below), where some used DPK, which produces longer cycle lengths at lower cycle rates than DP or DIA (Nilsson et al., 2004). Our detailed analysis here reveals that usage of DPK alone or in combination with DP or DIA resulted in lower cycle rates than with the other techniques, for both the female and male skiers.

Influence of sex and level of performance on cycle characteristics and external power output

There were sex differences in all of the variables measured, with the male skiers exhibiting higher cycle velocities, longer cycles at lower rates, shorter poling phases, but longer pole swing times. Their shorter poling times can be attributed to their higher skiing speeds (Hebert-Losier et al., 2017; Stöggl and Holmberg, 2016; Stöggl et al., 2011; Stöggl and Müller, 2009). Comparison of the FS and SS resulted in a highly similar pattern, except for a higher cycle rate for the FS and lack of any difference in pole swing time, again attributable to the differences in cycle velocity. In agreement, during the 30-km classical Olympic race in Lillehammer in 1994 Smith and co-workers (1996) observed higher cycle velocities and a trend towards longer cycles by faster female skiers on the slightly downhill terrain.

The greatest absolute sex differences were observed in cycle velocity and cycle length on flat terrain, with these differences narrowing as the incline rose (Figure 2). However, in relationship to the relative differences, this interaction was no longer significant. The most pronounced relative sex differences were in cycle velocity on the intermediate terrain (23.3%) and cycle length on the steep uphill terrain (27.0%).

In connection with incremental treadmill tests at peak speed, Sandbakk et al. (2014) observed the largest sex differences when performing DP (20%), followed by G3 skating (17%), DIA (14%) and treadmill running (12%). Similarly, Hegge and co-workers (2016) demonstrated that requirement for a greater contribution by the upper body (achieved with various modifications of a DP ski ergometer) accentuates the differences in external power output by men and women. On the basis of these findings, greater sex differences would be expected on the flat-to-moderate uphill sections of a XC race course, where DP is the primary technique used. However, during on-snow racing we found the most pronounced relative sex differences on intermediate terrain (where a mixture of techniques was employed) and on the steeper uphill sections (where DIA was used almost exclusively). Apparently, sex differences observed in connection with laboratory tests are not necessarily the same as for real XC ski races on snow.

Choice of technique on intermediate terrain

On intermediate terrain our male skiers utilized DP and DPK to a greater extent, whereas the women more often chose DPK or DIA. It is noteworthy that only two male SS employed DIA. Furthermore, better performance was associated with more extensive use of DPK and less of DIA, which is in line with the recent findings on the performance of male skiers during the first versus the second half of a 15-km classical XC skiing race (Welde et al., 2017). Accordingly, Stöggl and colleagues (2007) demonstrated that during a simulated classical sprint skiing race on a treadmill, the faster skiers employed fewer cycles and tended to use DP and DPK to a greater extent.

This difference might reflect the greater upper-body capacity and strength of FS and male skiers, prerequisites for successful application of the DPK and DP techniques on intermediate terrain. Another explanation might certainly be the lower skiing speeds of the female and SS, which might be associated with skiing techniques of lower gear (e.g. DIA, DPK and DP resemble low-to-high gears during cycling or a vehicle). The revolutionary expansion of DP usage by elite skiers (Hebert-Losier et al., 2017; Stöggl and Holmberg, 2016; Stöggl and Holmberg, 2011) also supports this conclusion. Indeed, the fastest of our male skiers employed DP exclusively along the entire course, demonstrating the considerable potential of this technique.

The male skiers in our study performed fewer transitions on intermediate terrain than the women, indicating that the men were able to maintain a single technique on terrain that allowed the application of various techniques. At the same time, this difference may reflect the women's uncertainty regarding the best technique to use on this intermediate terrain and/or that they were closer to their threshold for transitions between techniques on this incline. In this context, Pellegrini and colleagues (2013) showed that during classical roller skiing on a treadmill, skiers switched from DP to DPK at an incline of 2-3°, while all skiers employed DIA on inclines >6°. In that investigation, none of the skiers chose DP when the incline was >4°. The influence of incline and speed on the choice of technique either during roller skiing (Stöggl et al., 2007, Pellegrini et al., 2013) or skiing on flat (Bilodeau et al., 1996; Smith et al., 1996) and steeper uphill terrain (Bilodeau et al., 1996) has been clearly established. The current investigation provides novel insights into the choice of technique during classical XC racing on snow on intermediate terrain.

Cycle characteristics and total race performance

The cycle velocities on steep uphill and intermediate terrain provided the best predictors of race outcome for our female skiers, whereas the cycle velocities on flat, followed by steep uphill and uphill terrain gave the best predictors in the case of the men. In general, more than 50% of the total time during XC distance races is spent skiing uphill and, consequently, uphill performance is regarded as the major determinant of success (Bergh and Forsberg, 1992; Bilodeau et al., 1996; Bolger et al., 2015; Mognoni et al., 2001; Norman and Komi, 1987; Sandbakk et al., 2016). Here, however, this was only the case for the female skiers, in agreement with a recent report by Sandbakk et al. (2016) that the time spent on uphill is the best predictor of the outcome of a 10-km race in females. For the men in our study the best predictor of V_{Race} was the time spent on flat terrain, again emphasizing the considerable importance of DP performance in connection with modern XC competitions, especially for men.

In addition to the cycle velocity, the only other variable with a significant impact on the regression model was cycle length, which was related to performance by the women on intermediate-to-steep uphill terrain and by the men on flat, uphill and steep uphill terrain. In addition, the medalists demonstrated clearly higher cycle velocity and longer cycles than the remaining skiers. Here, higher cycle rate was associated with better performance only for female skiers on the steep uphill terrain. However, the cycle rate of the female medalists did not differ from that of the other 38 female skiers.

In contrast, on the steep and very steep uphill sections the three male winners employed a higher cycle rate than the other 38. These observations are consistent with previous findings concerning the importance of cycle length during both classical XC races and treadmill roller-skiing at high speeds (Bilodeau et al., 1996; Björklund et al., 2015; Holmberg et al., 2005; Norman and Komi, 1987; Smith et al., 1996; Stöggl et al., 2011; 2013; Stöggl and Holmberg, 2011), but somewhat in contrast to previous reports of lower (Norman and Komi, 1987) or similar cycle rates (Smith et al., 1996; Bilodeau et al., 1996) in faster and slower elite female skiers. It is noteworthy that in the present case, but in none of these other studies an incline of 11° was examined.

Finally, our female medalists weighed approximately 5 kg more and were able to produce a distinctly higher power output than the remaining female skiers. This difference might reflect a more athletic body composition, with higher total mass and especially muscle mass that might have resulted in higher skiing velocities and, consequently, more power output. A high percentage of lean mass (with a special focus on increased trunk muscle mass) has already been shown to be important in this context, especially for DP performance (Stöggl et al., 2010). This result might also indicate the potential for women to enhance their XC skiing performance by increasing their muscle mass further, whereas men appear to have already exploited this potential.

Limitations

One limitation here is that in our analysis of the intermediate section/terrain, various techniques and combinations thereof were pooled. Since DP on such terrain is characterized by a shorter cycle length and higher cycle rate than DPK and DIA, analyzing these together influences the variability of certain of the kinematic parameters. However, one major finding here is that on this intermediate section/terrain the individual techniques employed varied widely, motivating our approach to comparing the cycle characteristics associated with the different inclines.

With regards to our power calculations, possible differences in the drag area of individual or female and male skiers were not considered. Secondly, a standard coefficient of friction was applied, although this might have been differed for the different types of skis, grinds, glide and grip wax applied. A final limitation is the simple 2D video measurements employed, although full HD video quality was used and the classical XC skiing techniques involve primarily movements in the sagittal plane.

Conclusions

In conclusion, in the current investigation we have analyzed in detail the choice of technique, cycle characteristics and external power output by elite female and male skiers on various inclines during a classical XC distance race on snow. It was demonstrated that an increase in the incline affected all cycle characteristics assessed with reductions in cycle velocity, cycle length and pole swing time, an increase in external power output and a J-shaped pattern in the case of cycle rate. The men differed from the women in all respects, with higher cycle velocity, longer cycles, lower cycle rate, shorter poling and relative pole swing times, and higher external power output. In this context the largest absolute sex differences in cycle velocity and length were observed on flat terrain (using DP), with these differences narrowing as the incline increased. However, the greatest relative sex differences in cycle velocity and length were found on intermediate and steep uphill terrain, respectively.

There were similar differences between the two performance groups, with faster skiers utilizing longer and more rapid cycles than slower skiers. While all the skiers employed similar techniques on the flat (DP) and uphill terrain (DIA; with the exception of the male winner who used DP exclusively throughout the race), there was considerable variation on the intermediate section, where the men employed DP and DPK to a greater extent with fewer transitions than the female skiers. Furthermore, faster skiers (especially women) utilized DP and DPK to a greater and DIA to a lesser extent compared with the slower skiers.

Cycle velocity on flat terrain was the best predictor of mean race velocity for the men, while cycle velocity on steep uphill terrain was the best predictor in the case of women.

Future biomechanical characterization in this field should focus on, e.g., the influence of choice of strategies on different terrains, the effects of training of appropriate strength and endurance, and potential differences between male and female skiers in such respects. Moreover, similar characterization of other endurance sports, such as biathlon, mountain-biking, and XC running would also be beneficial. The rapid development of wearable sensors that can provide continuous and immediate information concerning a variety of parameters opens invaluable new approaches to such research, as well as providing important real-time feedback to both athletes and their coaches.

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Key points

- There was a main effect of sex and level of performance, with longer and more rapid cycles by male than female skiers and by faster than slower skiers.
- The largest absolute sex differences in cycle velocity and length were observed on flat terrain, with these differences narrowing as the incline rose. However, the greatest relative sex differences were in cycle velocity on the intermediate terrain (23.3%) and for cycle length on steep uphill terrain (27.0%).
- The men employed DP and DPK to a greater extent and with fewer transitions on intermediate terrain than the women. Faster skiers (especially women) employed DPK to a greater and DIA to a lesser extent than the slower skiers, with approximately equal usage of DP.
- Cycle velocity on flat terrain was the best predictor of mean race velocity for the men, while cycle velocity on steep uphill terrain was the best predictor in the case of the women.
- As the incline increased, cycle velocity, cycle length and pole swing time were reduced, while poling time and external power output rose. A J-shaped pattern with respect to cycle rate was observed, with the lowest values on intermediate and highest on steep uphill terrain.

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