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Biomechanical differences in double poling between sexes and level of performance during a classical cross-country skiing competition

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ABSTRACT

Biomechanical differences in double poling (DP) between sex and performance level were investigated in female and male cross-country skiers during a classical race (10/15 km). Skiers were divided into faster and slower on basis of race performance: females faster (n=20), females slower (n=20), males faster (n=20), and males slower (n=20). Based on video analysis while DP in a flat section of the track, joint and pole angles at pole plant (PP) and pole-off, cycle characteristics and the use and coordination pattern of heel-raise (raise of heels from the ground to have a higher body position at PP) were analysed. Faster females and males had 4.3% and 7.8% higher DP velocity than their slower counterparts (both $P<0.001$). Faster males had 6.5% longer cycles than slower males ($P<0.001$). Faster skiers stopped heel-raise later than slower skiers (females: 2.0±3.4% vs. −1.0±3.5%, $P<0.05$; males: 3.9±2.4% vs. 0.8±3.2% of cycle time in relation to PP, $P<0.001$). At PP, faster skiers and male skiers had a smaller pole angle and greater ankle to hip and ankle to shoulder angle with respect to vertical, resulting in a more distinct forward body lean. However, the majority of the differences are likely due to higher DP velocity.

ARTICLE HISTORY
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KEYWORDS
Cycle characteristics; heel-raise; joint angles; kinematics; pole angles; video analysis

Introduction

During classical cross-country (XC) skiing, double poling (DP) is the technique most often used on flat terrain. During the last decades, the importance of DP has increased, with some skiers exclusively using DP during entire races and skiers have started to adopt their DP technique to different speeds and inclines (Holmberg, Lindinger, Stöggl, Eitzlmair, & Müller, 2005; Lindinger, Stöggl, Müller, & Holmberg, 2009; Stöggl & Holmberg, 2011; Stöggl et al., 2018; Welde et al., 2017). This gradual change in the usage of the DP technique, may be a result of better preparation of the track, better equipment (including better grooming), an improved upper-body strength and improvements in skiing technique (Holmberg et al., 2005; Sandbakk & Holmberg, 2014; Stöggl & Holmberg, 2011, 2016).

During classical XC-competitions, the difference in skiing velocity between males and females was shown to be approximately 11% with the largest difference in speed at uphill terrain (14%) (Bolger, Kocbach, Hegge, & Sandbakk, 2015). In contrast, Sandbakk, Ettema, and Holmberg (2014) showed that there were greater sex differences in peak speed during DP (20% higher in males) compared to diagonal skiing (14%) while roller skiing on a treadmill. In line with this, it is shown that sex differences in power output increase where increasing upper-body contribution is required (Hegge et al., 2016; Sandbakk et al., 2014). Within the DP technique at peak speeds, cycle lenght (CL) is higher in males than in females (+23%), with no difference in cycle rate (CR) (Sandbakk et al., 2014). This might be a result of the higher relative muscle mass in the upper-body in males compared to females, with the largest sex difference in the arms (Hegge et al., 2016; Janssen, Heymsfield, Wang, & Ross, 2000).

Earlier studies have shown that during DP, faster skiers are creating longer CL (Stöggl & Holmberg, 2011; Stöggl, Lindinger, & Müller, 2007), longer swing times (ST) (Stöggl & Holmberg, 2011; Stöggl & Müller, 2009) and are covering a longer distance during the poling phase (Stöggl & Holmberg, 2011, 2016) than slower skiers. From a physiological perspective, Stöggl, Björklund, and Holmberg (2013) showed that longer CL, longer absolute ST and the absolute DP velocity at 90% of VO_{2max} ("competition speed"), were associated with a higher oxygen extraction in arms and/or legs than at 70% of VO_{2max}.

Some research groups have already identified certain biomechanical parameters that are related to DP performance. It was demonstrated, that faster skiers (according to race performance, and/or peak DP velocity and/or performance level) applied a DP technique that is characterized by a more advantageous body position prior to and at the instant of the pole plant (PP), to consecutively generate effective pole forces during the poling phase. Specifically, prior to PP faster skiers demonstrated (1) a greater displacement in forward direction of the poles (vertical and horizontal) during the last part of the swing phase (being defined as the "preparation point") (Stöggl & Holmberg, 2011, 2016), (2) a greater forward lean of the whole body at PP and during the early part of the poling phase (Zoppirolli, Pellegrini, Bortolan, & Schena, 2015), combined with (3) more vertical planted poles (Smith, Fewster, & Braudt, 1996; Stöggl & Holmberg, 2011; Zoppirolli et al.,

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2015) and, (4) greater covered distance of the poles with respect to the toecap/pivot point both at PP and pole-off (PO) (Stöggl & Holmberg, 2011, 2016). However, all the above-mentioned investigations (except from the study by Smith and colleagues) were performed in the laboratory while roller skiing on a treadmill.

During the last 20 years, biomechanical analysis of DP during on-snow competitions, have only been made in two studies (Zoppirolli et al., 2018; Zory, Vuillerme, Pellegrini, Schena, & Rouard, 2009). In both the effect of fatigue on kinematics in DP was investigated. To our knowledge, the last study investigating biomechanical differences in DP between skiers at different performance level during a competition was Smith et al. (1996). In two recent publications within our research group, the effects of incline (Stöggl et al., 2018) and fatigue (Welde et al., 2017) on cycle kinematics, during the same XC skiing competition, were presented. In this latter study, skiing velocity on flat and intermediate terrain proved to be the best predictors of race performance, which highlights the significance of the DP technique for overall XC skiing success. However, detailed analysis of the DP kinematics (body angles, timing, heel-raise) were not scope of these studies.

Moreover, it is common in elite skiers to use heel-raise during DP (Stöggl & Holmberg, 2011); meaning that during the swing phase, the skier raises his/her heels from the ground in order to have a higher body position at PP. During the swing phase, the skier needs to reposition the body and to elevate the centre of mass in order to put more body weight on the poles at PP (Holmberg et al., 2005; Losnegard, Myklebust, Ehrhardt, & Hallen, 2017; Zoppirolli et al., 2015). By using heel-raise this effect might be even larger. Stöggl and Holmberg (2016) were the first to report that male elite skiers were using heel-raise when DP both uphill and on flat terrain and that the magnitude of the heel-raise was correlated to maximal DP speed when skiing uphill. However, the duration and timing of heel-raise for both sexes and different levels of performance have not been analyzed in any of the above-mentioned studies.

The purpose of the present study was to characterize biomechanical differences in DP by comparing male and female, faster and slower XC-skiers of elite performance level during a 10/15 km classical competition. The biomechanical factors of interest were cycle characteristics, pole and body angles, and the use of heel-raise. Based on findings during both roller skiing and on-snow skiing, we hypothesized that the faster skiers and males demonstrate longer cycles, with a greater body forward inclination and a greater use of heel-raise than slower skiers, respectively females at similar CR.

Methods

This analysis of the performance and kinematics of elite male and female XC-skiers was conducted in connection with the 10-km (females) and 15-km (males) classical race at the Norwegian National Championship in Tromsø, 2016. The study was pre-approved by the *NSD Data Protection Official for Research* in Norway and the subjects were fully informed of its nature before providing their verbal consent to use their data.

The competitors were video recorded on a flat section (22 m in length and a mean incline of −0.3°) during the first lap after 0.8 km of the race. A high-speed video camera (Panasonic GH4, 96 Hz, shutter speed 1/500 s) atop a tripod placed on a custom-made wooden platform video recorded the skiers at high resolution (1920 x 1080 progressive scan). The camcorder was positioned 1 m above the ground and perpendicular to the track, levelled with an electronic inclinometer, and recorded in the sagittal plane from a distance of 25 m. The ski track was in the centre of the field of vision and the focus and zoom set to cover at least three cycles of movement within the measurement section. The calibration of the field of measurement were made according to Welde et al. (2017) and Stöggl et al. (2018). None of the skiers changed track within the video-recording site. The effects of lenses distortions can be assessed as minor, based on the long distance between the camera and the cite of interest, and the neglecting of the left and right edges of the video-picture (entrance and exit of the skiers into the video section) for kinematic analysis.

Prior to the race, each skier performed his/her own personal warm-up optimized for a classical 10 or 15-km race. All skiers used their own racing poles and skis, selected for the prevailing snow conditions and waxed (grip wax: base and violet/universal klister; gliding wax: high flour paraffin wax combined with flour powder) by experienced technicians. During the competition, the weather was stable, with no wind and air and snow temperatures of +1 and 0°C, respectively, and a relative humidity of 86%. The course was prepared with a grooming machine on the evening prior to the race and the team coaches considered the track conditions to be good, with no problems choosing the optimal wax.

Following the race, 40 participants of each sex (in total 80 skiers) were selected on the basis of their race performance and divided into faster (n = 20) and slower (n = 20) skiers. Hence, there were four groups in total: females faster (height: 168.2 ± 5.5 cm, weight: 61.9 ± 5.0), females slower (height: 169.0 ± 7.2 cm, weight: 64.0 ± 6.9 kg), males faster (height: 183.1 ± 4.3 cm, weight: 78.2 ± 4.1 kg) and males slower (height: 183.4 ± 5.1 cm, weight: 77.4 ± 5.7 kg). The faster skiers (including five who ranked among the top 10 in the World Cup in 2016 and four medallists at World Championship or Olympic Games) all had finishing times within 8% (males) and 11% (females) of that of the winner, whereas the slower skiers were 10–16% (males) and 14–22% (females) slower than the winner.

Data analysis

The total racing time was obtained from the race organizers, while mean DP velocity, cycle characteristics, distances and selected joint angles within the flat section were determined from the 2D video recordings and analysed using the Kinovea software (version 8.25, France). For all variables the mean of at least three cycles were taken for further statistical analysis. A full cycle was defined as the period of time between two consecutive PP, i.e. when the poles were visibly taking contact with the snow. The poling phase was defined as the part of the cycle when the poles were visibly having contact with the snow (until the poles were visibly losing contact with the snow, PO) and the rest of the cycle was called swing phase.

Both the absolute and the relative poling/swing times were calculated. The distance between the pole and the skiers toe-cap was measured at PP and PO.

At PP, the following angles were measured: elbow, hip and knee angles (180°, full extension) and pole, trunk, tibia, ankle to hip, ankle to shoulder and ankle to hand with respect to vertical plane (0°, parallel to vertical plane) (see Figure 1(a)). If the hip was behind the vertical line, the angle between ankle to hip was presented with negative values. At PO, the elbow, hip and knee angle and the pole, trunk, and tibia angle with respect to vertical were measured (see Figure 1(b)). Finally, the minimum angles for the trunk, knee and elbow during the poling phase and the angle and instant in time of the pole at "preparation point" (if the pole tip was in front of the vertical line, the angle was presented with negative values) during the swing phase was measured (Stöggl & Holmberg, 2011, 2016).

During DP, some participants were lifting their heels during the poling cycle, called "heel-raise". The start of the heel-raise was defined when the participant visibly started to lift the heels from the ski and ended when the heels were taking contact with the ski again. Both the duration of the heel-raise, and the timing when the heel-raise started and stopped in relation to PP were analysed.

Statistical analysis

All data showed normal distribution according to the Shapiro-Wilk test and are presented as mean ± standard deviations (SD). Two way ANOVA (sex x level) was used to find differences between the four groups (females faster, females slower, males faster, males slower) applying Bonferroni α correction. Moreover, to control for the potential effects of DP velocity (i.e. correlation between DP velocity and mean race speed), a two way ANCOVA (sex x level) with DP velocity as the covariate variable was used. Hence, we could inspect the variance in the relevant dependent variable explained by the covariate, the categorical independent variables, and the residual variance. To determine relationships between measured variables and DP velocity, Pearson's Product Moment Correlation were used. To test for significance of the difference between two correlation coefficients (i.e. females vs. males on the same variables), the Fisher r-to-z transformation was applied. Furthermore, a partial correlation analysis ($r_{xy\text{-}z}$) with sex as a confounder was performed. For the statistical analysis between the subgroup of skiers that used heel-raise, independent sample t-tests were performed. The statistical level of significance was set at $\alpha < 0.05$ for all analyses. All statistical tests were processed using SPSS 24.0 Software (SPSS, Inc., Chicago, IL) and Office Excel 2003 (Microsoft Corporation, Redmond, WA).

Results

Performance and cycle characteristics

The faster skiers had a 9.5% (females) and 7.0% (males) higher mean race speed than the slower skiers (females: 5.50 ± 0.16 vs. 4.98 ± 0.12 m/s, males: 6.30 ± 0.12 vs. 5.86 ± 0.09 m/s, both $P < 0.001$). The mean DP velocity and cycle characteristics within the DP section for females and males, and faster and slower skiers are shown in Table 1. For the group in total there was a positive correlation between mean race speed and DP velocity ($r = 0.89$, $P < 0.001$, Figure 2), with a stronger correlation for males than for females ($r = 0.81$ vs. $r = 0.49$, both $P < 0.001$; difference: $z = 2.54$, $P < 0.01$). With sex as a confounding variable, the correlation was still significant ($r_{xy\text{-}z} = 0.66$, $P < 0.001$).

Following ANCOVA (with DP velocity as covariate), there were still a difference between male and female skiers according to CT, CR, CL (all $P < 0.001$) and absolute ST ($P = 0.005$). Also a difference in CT ($P = 0.031$), CR ($P = 0.028$) and CL ($P = 0.037$) occurred between the faster and slower groups of skiers.

Pole and joint angle kinematics

The female skiers had a shorter distance between pole tip and the toecap at PP and PO than the male skiers (27% and 8% shorter) resulting in a 13.7% shorter total distance covered for each DP poling phase (1.83 ± 0.12 vs. 2.08 ± 0.11 m, $P < 0.001$). The female skiers had a smaller angle at PP for tibia ($P < 0.001$), ankle to hip ($P < 0.001$), ankle to shoulder ($P < 0.001$), ankle to hand ($P = 0.016$) (all with respect to vertical) and a larger knee angle ($P < 0.001$) (i.e. a more upright posture) then the male skiers. Furthermore, the female skiers had larger trunk

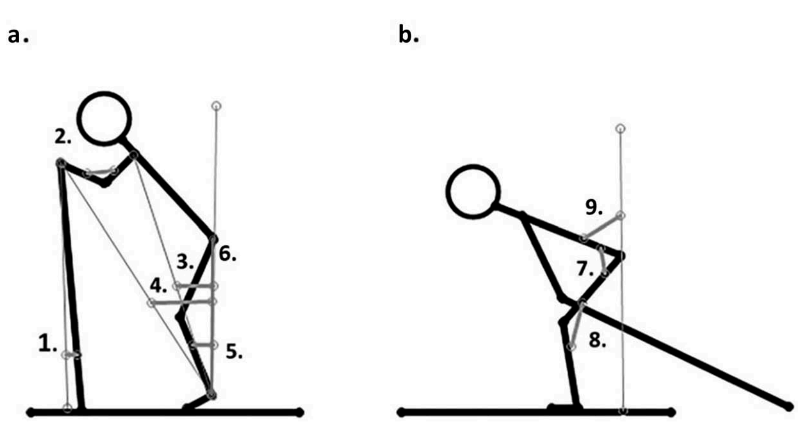

Figure 1. At pole plant (a) and pole-off (b) the following body angles were measured: pole angle in relation to vertical (1), elbow angle (2), ankle-shoulder to vertical (3), ankle-hand to vertical (4), tibia angle to vertical (5) and ankle-hip angle to vertical (6), hip angle (7) knee angle (8) and trunk angle to vertical (9).

Table 1. Cycle and pole characteristics for the four sub-groups of female and male cross-country skiers employing the double-poling technique on the flat section of the 10/15 km classical race at the Norwegian cross-country skiing championships in Tromsø, 2016.

	Females (N = 40)		Males (N = 40)		Total (N = 80)		Total (N = 80)	
Parameter	Faster (N = 20)	Slower (N = 20)	Faster (N = 20)	Slower (N = 20)	Females (N = 40)	Males (N = 40)	Faster (N = 40)	Slower (N = 40)
Double poling velocity (m/s)	6.30 ± 0.23bb^{bbb,ccc,ddd}	6.04 ± 0.25^{aaa,ccc,ddd}	7.42 ± 0.18^{aaa,bbb,ddd}	6.88 ± 0.29^{aaa,bbb,ccc}	6.17 ± 0.27	7.15 ± 0.36^{eee}	6.86 ± 0.60	6.46 ± 0.50^{ff}
Cycle time (s)	1.00 ± 0.09^{c,dd}	1.03 ± 0.08^{d}	1.08 ± 0.06^{a}	1.09 ± 0.05^{aa,b}	1.02 ± 0.09	1.09 ± 0.06^{eee}	1.04 ± 0.09	1.06 ± 0.07
Cycle rate (Hz)	1.00 ± 0.09^{cc,dd}	0.98 ± 0.08^{d}	0.93 ± 0.05^{aa}	0.92 ± 0.04^{aa,b}	0.99 ± 0.09	0.92 ± 0.05^{eee}	0.97 ± 0.08	0.95 ± 0.07
Cycle length (m)	6.33 ± 0.62^{ccc,ddd}	6.20 ± 0.53^{ccc,ddd}	8.00 ± 0.48^{aaa,bbb,d}	7.51 ± 0.39^{aaa,bbb,c}	6.27 ± 0.57	7.76 ± 0.50^{eee}	7.17 ± 1.01	6.85 ± 0.81
Poling time$_{abs}$ (s)	0.27 ± 0.01	0.28 ± 0.02^{c}	0.27 ± 0.02^{b}	0.27 ± 0.02	0.28 ± 0.02	0.27 ± 0.02	0.27 ± 0.01	0.28 ± 0.02^{f}
Poling time$_{rel}$ (%)	27.0 ± 2.5^{cc,d}	27.5 ± 2.7^{cc,dd}	24.7 ± 1.6^{aa,bb}	24.9 ± 1.5^{a,bb}	27.2 ± 2.6	24.8 ± 1.5^{eee}	25.8 ± 2.4	26.2 ± 2.5
Swing time$_{abs}$ (s)	0.74 ± 0.09^{cc,dd}	0.75 ± 0.08^{c,dd}	0.81 ± 0.06^{aa,b}	0.82 ± 0.04^{aa,bb}	0.74 ± 0.08	0.82 ± 0.05^{eee}	0.77 ± 0.08	0.78 ± 0.07
Swing time$_{rel}$ (%)	73.0 ± 2.5^{cc,d}	72.5 ± 2.7^{ccc,dd}	75.3 ± 1.7^{aa,bbb}	75.1 ± 1.4^{a,bb}	72.8 ± 2.6	75.2 ± 1.5^{eee}	74.2 ± 2.4	73.7 ± 2.4
Distance pole-toe PP (m)	0.33 ± 0.07^{ccc,d}	0.32 ± 0.11^{ccc,d}	0.48 ± 0.07^{aaa,bbb}	0.40 ± 0.09^{a,b}	0.32 ± 0.09	0.44 ± 0.09^{eee}	0.40 ± 0.10	0.36 ± 0.11
Distance pole-toe PO (m)	1.52 ± 0.06^{ccc,ddd}	1.50 ± 0.09^{ccc,ddd}	1.63 ± 0.10^{aaa,bbb}	1.65 ± 0.07^{aaa,bbb}	1.51 ± 0.07	1.64 ± 0.09^{eee}	1.58 ± 0.10	1.58 ± 0.11
Poling distance/cycle (m)	1.85 ± 0.10^{ccc,ddd}	1.82 ± 0.14^{ccc,ddd}	2.11 ± 0.12^{aaa,bbb}	2.05 ± 0.10^{aaa,bbb}	1.83 ± 0.12	2.08 ± 0.11^{eee}	1.98 ± 0.17	1.94 ± 0.17

All values are presented as means ± SD. PP, pole plant; PO, pole-off.
[a] = significantly different from the corresponding value for the faster group females, P < 0.05, [aa] = P < 0.01, [aaa] = P < 0.001.
[b] = significantly different from the corresponding value for the slower group females, P < 0.05, [bb] = P < 0.01, [bbb] = P < 0.001.
[c] = significantly different from the corresponding value for the faster group males, P < 0.05, [cc] = P < 0.01, [ccc] = P < 0.001.
[d] = significantly different from the corresponding value for the slower group males, P < 0.05, [dd] = P < 0.01, [ddd] = P < 0.001.
[e] = significantly different from the corresponding value for the females, P < 0.05, [ee] = P < 0.01, [eee] = P < 0.001.
[f] = significantly different from the corresponding value for the faster group, P < 0.05, [ff] = P < 0.01, [fff] = P < 0.001.

(P = 0.015), and pole to vertical angles (P < 0.001) and smaller hip angles (P = 0.003) at PP compared to the males (Figure 3). After ANCOVA (with DP velocity as covariate), the only differences between the sexes were that the female skiers had a smaller hip angle at PP and PO (P = 0.008 and P = 0.009), a smaller distance between the pole tip and the toecap at PO (P < 0.001) and a shorter poling distance for each DP cycle (P < 0.001) compared to the male skiers.

At PP, the faster skiers in total had a smaller pole angle (P = 0.28), and a larger angle in both ankle to hip (P = 0.004) and ankle to shoulder in relation to vertical (P = 0.028) (more forward body lean) compared to the slower skiers, with no difference between the groups for distance between pole and toecap. These differences were no longer present after the ANCOVA-analyses with DP velocity as a covariate.

For the male skiers, at PP the faster group had a smaller pole angle with respect to vertical compared to the slower skiers (P = 0.012). For the female skiers, the faster group had a greater ankle to hip and ankle to shoulder angle with respect to vertical (more forward body lean) compared to the slower group (P = 0.041 and P = 0.026), with no other difference in joint angles (Table 2).

During the swing phase, the preparation point occurred 5.3–6.3% of cycle time (CT) before PP with no difference between the groups in either maximal pole angle or the timing of it (1.4 ± 6.7° in relation to vertical and 62 ± 38 ms before PP for the group in total). All analysed skiers demonstrated a preparation phase.

Heel-raise

Twenty-seven of the female skiers (15 faster and 12 slower) and 39 of the male skiers (19 faster and 20 slower) used heel-raise. There were no differences for when the heel-raise started between the female and male skiers (24.1 ± 7.8 vs. 28.2 ± 8.9% of CT before PP), or between the faster and slower groups (28.5 ± 10.9 vs. 24.4 ± 4.7% of CT before PP) (both P > 0.05). Within the male skiers that used heel-raise, it started earlier in the faster group compared with the slower skiers (32.2 ± 10.7% vs. 24.4 ± 4.4% of CT before PP, P = 0.002) with no such difference within the female skiers (23.9 ± 9.6% and 24.4 ± 5.3% of CT before PP, P > 0.05). The stop of the heel-raise was later for the faster than the slower skiers with no difference between the sexes (females; 2.0 ± 3.4% vs. −1.0 ± 3.5% of CT in relation to PP, P = 0.030; males: 3.9 ± 2.4% vs. 0.8 ± 3.2% of CT after PP, P = 0.002).

The absolute and relative (% of CT) duration of the heel-raise were longer for males compared to females (0.32 ± 0.08 vs. 0.24 ± 0.07 s, P < 0.001; 29.3 ± 7.5% vs. 24.0 ± 6.9% of CT, P = 0.004) and for the faster compared to the slower skiers (0.31 ± 0.10 vs. 0.26 ± 0.06 s, P = 0.020; 29.6 ± 8.5% vs. 24.5 ± 5.7% of CT, P = 0.006).

For the female skiers there was no difference in DP velocity between those who used heel-raise compared with those that did not. No such comparison was made for the male skiers, because only one man did not use heel-raise during the DP section.

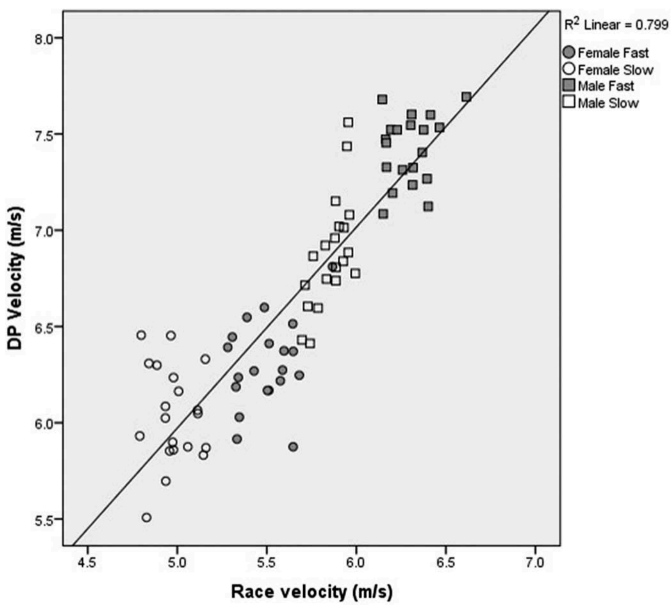

Figure 2. The relationship between double poling velocity and mean race velocity during the 10/15 km classical race at the Norwegian cross-country skiing championships in Tromsø, 2016 for the four sub-groups of skiers (N = 20 for each group, in total N = 80).

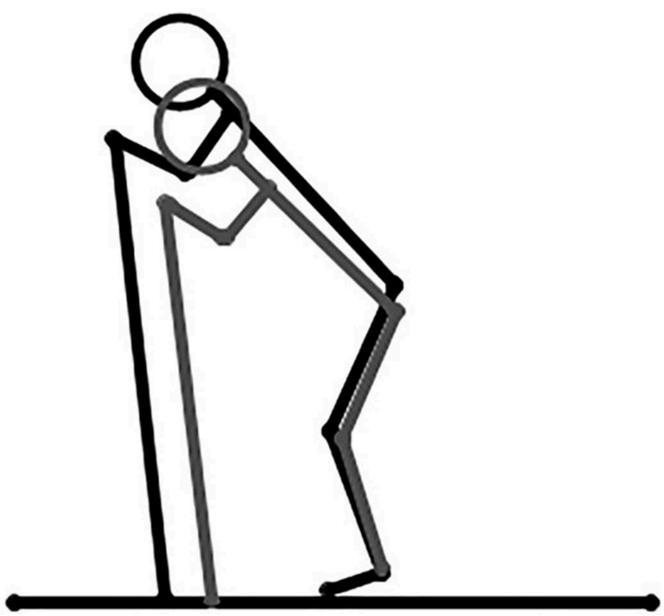

Figure 3 . Mean body position during pole plant for the female (grey lines) and male (black lines) skiers. The skiers are scaled according to mean body height.

Correlations

For the DP velocity, there was a positive correlation for the group in total for CL (r = 0.84, $P < 0.001$, Figure 4), ST (absolute r = 0.40, relative r = 0.56, both $P < 0.001$), distance between toecap and pole tip at PP and PO (r = 0.55 and r = 0.54, both $P < 0.001$) and for tibia angle (r = 0.55, $P < 0.001$), ankle to hip angle (r = 0.56, $P < 0.001$) and ankle to shoulder angle at PP (r = 0.45, $P < 0.001$). The DP velocity was negatively correlated to PT (absolute r = −0.42, relative r = −0.56, both $P < 0.001$) and pole angle at PP (r = −0.48, $P < 0.001$) (Table 3). For the group in total, the stop of the heel-raise was correlated to DP velocity (r = 0.37, P = 0.003). For the male and the female skiers, the stop of the heel-raise was correlated with DP velocity (males: r = 0.47, P = 0.002; females r = 0.47, P = 0.013).

After the partial correlation analysis with sex as a confounder, the remaining variables correlating with DP velocity were CL (r_{xy-z} = 0.52, $P < 0.001$), PT (absolute r_{xy-z} = −0.57, $P < 0.001$, relative r_{xy-z} = −0.25, P = 0.044), relative ST (r_{xy-z} = 0.26, P = 0.035), distance between toecap of the shoe and pole tip at PP (r_{xy-z} = 0.26, P = 0.035), tibia angle (r_{xy-z} = 0.26, P = 0.039) and ankle to shoulder angle at PP ($_{xy-z}$ = 0.27, P = 0.027).

Discussion

The main findings of this study were as follows: (1) DP velocity was positively associated to mean race speed, (2) 82% of the skiers used a heel-raise, which started approximately 26% of CT prior to PP and ended 2% after PP within the poling phase, (3) faster skiers ended their heel-raise later than slower skiers with no difference between the two groups in when the heel-raise started, (4) faster skiers demonstrated more vertically planted poles and a more pronounced whole body forward lean at PP compared to the slower skiers, (5) CL, ST (absolute and relative), distance between pole and toecap at PP and PO, and tibia and ankle to shoulder angle with respect to vertical at PP (more forward lean advantageous) was positively correlated to DP velocity while PT (absolute and relative), and pole angle to vertical at PP was negatively correlated to DP velocity and, finally, (6) the female skiers had a higher CR, a shorter CL and a longer relative poling phase than the male skiers.

Race performance

In the current study higher DP velocity was associated with better total race performance which is in line with the findings of Smith et al. (1996) in female XC skiers during the 1994 Lillehammer Olympic 30-km race. Worth mentioning, that in the present study, the correlation between DP velocity and race speed was stronger for the male than for the female skiers. To be added here, that during this Norwegian championships one male skier was using exclusively the DP technique during the entire 15 km classical race and he was also the winner of the race with 52.6 s ahead of the second ranked skier.

Heel-raise

The current study demonstrates that a large percentage of XC skiers are using heel-raise during DP (approximately 82% of the skiers) and this is to our knowledge the first report about this technical feature during on-snow skiing, in both sexes, and on the time coordination of it. In the current study, the heel-raise started approximately 26% prior to PP and ended 1–2% after PP. Only one male skier did not use heel-raise within the analysed DP section while 67% of the females used heel-raise. To be added here, that within the females the use of a heel-raise did not discriminate between

Table 2. Joint and pole kinematics at pole plant and pole off for the four sub-groups of female and male cross-country skiers employing the double-poling technique on the flat section of the 10/15 km classical race at the Norwegian cross-country skiing championships in Tromsø, 2016.

Parameter	Females (N = 40)		Males (N = 40)		Total (N = 80)		Total (N = 80)	
Angles at pole plant	Faster (N = 20)	Slower (N = 20)	Faster (N = 20)	Slower (N = 20)	Females (N = 40)	Males (N = 40)	Faster (N = 40)	Slower (N = 40)
Poles to vertical (°)	7.4 ± 2.1^{ccc}	7.8 ± 3.1^{ccc}	$3.5 \pm 2.4^{aaa,bbb,d}$	6.1 ± 2.4^{c}	7.6 ± 2.6	4.8 ± 2.7^{eee}	5.6 ± 3.0	7.0 ± 2.9^{f}
Tibia to vertical (°)	$16.9 \pm 4.5^{c,d}$	$13.3 \pm 3.4^{ccc,ddd}$	$21.3 \pm 5.2^{a,bbb}$	$21.3 \pm 5.9^{a,bbb}$	15.1 ± 4.3	21.3 ± 5.5^{eee}	19.1 ± 5.3	17.3 ± 6.2
Trunk to vertical (°)	45.0 ± 3.5	44.9 ± 4.1	42.1 ± 3.4	43.6 ± 3.4	44.9 ± 3.7	42.8 ± 3.4^{e}	43.5 ± 3.7	44.3 ± 3.8
Ankle-hip to vertical (°)	$-1.6 \pm 3.1^{b,ccc}$	$-4.1 \pm 2.6^{a,ccc,ddd}$	$2.2 \pm 2.5^{aaa,bbb}$	0.1 ± 3.3^{bbb}	−2.9 ± 3.1	1.2 ± 3.1^{eee}	0.3 ± 3.4	-2.0 ± 3.7^{ff}
Ankle-shoulder to vertical (°)	17.0 ± 1.8^{b}	$15.0 \pm 1.5^{a,ccc,ddd}$	18.1 ± 2.1^{bbb}	17.7 ± 2.9^{bbb}	16.0 ± 1.9	17.9 ± 2.5^{eee}	17.6 ± 2.0	16.4 ± 2.6^{f}
Ankle-hand to vertical (°)	30.0 ± 2.6	29.7 ± 2.1	30.7 ± 1.8	31.4 ± 2.9	29.9 ± 2.3	31.1 ± 2.4^{e}	30.4 ± 2.2	30.6 ± 2.6
Elbow (°)	102.5 ± 5.9	99.2 ± 10.1	96.1 ± 8.7	98.3 ± 8.4	100.8 ± 8.3	97.2 ± 8.5	99.3 ± 8.0	98.7 ± 9.2
Hip (°)	105.7 ± 8.7^{ccc}	109.6 ± 6.5	114.1 ± 5.9^{aaa}	111.1 ± 5.3	107.6 ± 7.8	112.6 ± 5.8^{ee}	109.9 ± 8.5	110.3 ± 5.9
Knee (°)	139.4 ± 4.3	143.7 ± 5.2	137.4 ± 6.8	133.5 ± 5.9	141.6 ± 5.2	135.4 ± 6.6^{eee}	138.4 ± 5.7	138.6 ± 7.5
Angles at pole off								
Poles to vertical (°)	66.6 ± 2.1	66.3 ± 1.5	65.3 ± 1.7	66.0 ± 2.1	66.4 ± 1.8	65.6 ± 1.9	65.9 ± 2.0	66.1 ± 1.8
Tibia to vertical (°)	6.5 ± 3.1	6.4 ± 3.9	4.9 ± 2.8	4.8 ± 3.9	6.5 ± 3.5	4.9 ± 3.3^{e}	5.7 ± 3.0	5.6 ± 3.9
Trunk to vertical (°)	68.4 ± 3.8	66.7 ± 5.3	67.2 ± 3.0	67.0 ± 6.4	67.6 ± 4.6	67.1 ± 4.9	67.8 ± 3.4	66.8 ± 5.8
Elbow	157.7 ± 8.7	162.6 ± 6.0	162.5 ± 7.9	158.6 ± 8.0	160.2 ± 7.8	160.5 ± 8.1	160.1 ± 8.6	160.6 ± 7.3
Hip (°)	$62.7 \pm 5.2^{bb,dd}$	69.1 ± 6.4^{aa}	66.1 ± 5.2	68.8 ± 6.5^{aa}	65.9 ± 6.6	67.4 ± 6.0	64.4 ± 5.4	69.0 ± 6.4^{fff}
Knee (°)	127.1 ± 5.6	129.8 ± 7.0	129.9 ± 5.9	129.5 ± 6.1	128.5 ± 6.4	129.7 ± 5.9	128.5 ± 5.9	129.7 ± 6.5
Minimum angles								
Trunk to vertical (°)	70.8 ± 3.2	68.3 ± 4.8	69.0 ± 3.0	68.8 ± 5.9	69.6 ± 4.2	68.9 ± 4.6	69.9 ± 3.2	68.6 ± 5.3
Elbow (°)	$78.2 \pm 7.8^{cc,d}$	72.1 ± 8.2	68.5 ± 6.2^{aa}	70.2 ± 10.6^{a}	75.1 ± 8.5	69.4 ± 8.7^{ee}	73.4 ± 8.5	71.1 ± 9.4
Knee (°)	123.6 ± 5.5	127.7 ± 6.7	126.6 ± 5.9	125.0 ± 6.6	125.7 ± 6.4	125.8 ± 6.2	125.1 ± 5.8	126.4 ± 6.7
Maximum angles								
Poles to vertical before PP (°)	2.7 ± 8.5	3.4 ± 6.9	−1.3 ± 5.2	0.7 ± 5.2	3.1 ± 7.6	-0.3 ± 5.2^{e}	0.8 ± 7.2	2.1 ± 6.2

All values are presented as means ± SD. PP, pole plant; PO, pole-off.
^{a} = significantly different from the corresponding value for the faster group females, $P < 0.05$, ^{aa} = $P < 0.01$, ^{aaa} = $P < 0.001$.
^{b} = significantly different from the corresponding value for the slower group females, $P < 0.05$, ^{bb} = $P < 0.01$, ^{bbb} = $P < 0.001$.
^{c} = significantly different from the corresponding value for the faster group males, $P < 0.05$, ^{cc} = $P < 0.01$, ^{ccc} = $P < 0.001$.
^{d} = significantly different from the corresponding value for the slower group males, $P < 0.05$, ^{dd} = $P < 0.01$, ^{ddd} = $P < 0.001$.
^{e} = significantly different from the corresponding value for the females, $P < 0.05$, ^{ee} = $P < 0.01$, ^{eee} = $P < 0.001$.
^{f} = significantly different from the corresponding value for the faster group, $P < 0.05$, ^{ff} = $P < 0.01$, ^{fff} = $P < 0.001$.

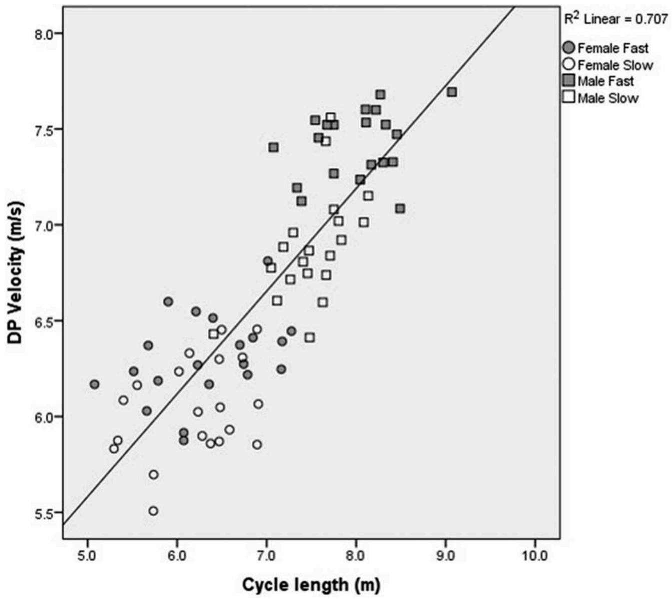

Figure 4. The relationship between double poling velocity and cycle length on the flat section of the 10/15 km classical race at the Norwegian cross-country skiing championships in Tromsø, 2016 for the four sub-groups of skiers (N = 20 for each group, in total N = 80).

the faster and slower female skiers. Furthermore, there was no difference between faster and slower skiers in total for when the heel-raise started, but the faster skiers stopped their heel-raise later than the slower skiers. Consequently, not the exact start of the heel-raise, but its well-time coordinated termination is relevant for DP performance. Based on the current results it is advised that the heel-raise should terminate later within the poling phase and not close (slightly before or after) to PP. During the swing phase, the legs are working to raise the centre of mass through a high position in the hip, to be able to put extra weight on the poles (Holmberg et al., 2005; Stöggl et al., 2013; Stöggl & Holmberg, 2016) and the use of heel-raise can help increase the body position even more. Consequently, based on the later stop of the heel-raise (most likely coupled with a lowering of the centre of mass) within the poling phase, the better skiers are possibly using their body weight in a more favourable way and might consequently create higher pole forces – an aspect, however that needs to be analysed in future studies. Stöggl and Holmberg (2011, 2016) have shown the importance of the timing of creating force during the poling phase with the faster skiers demonstrating a later time to peak pole force during a prolonged poling phase. The time of the peak pole force was also shown to be positively correlated to oxygen extraction in both arms and legs (Stöggl et al., 2013). This might have been linked also to the timing of the heel-raise, which however was not analysed within their studies.

Pole and joint kinematics

The female skiers had less vertically planted poles, a smaller angle in hip and tibia, ankle to hip, ankle to shoulder, ankle to hand and trunk (all in relation to vertical) and a larger knee angle at PP compared with the male skiers, which in total gives a more upright body position for the female skiers (see

Table 3. Relationships between double poling velocity and cycle characteristics/measured angles for the sex and performance level of cross-country skiers employing the double-poling technique on a flat section of the 10/15 km classical race at the Norwegian cross-country skiing championships in Tromsø, 2016.

	Double poling velocity.				
	Females (N = 40)	Males (N = 40)	Faster (N = 40)	Slower (N = 40)	Total (N = 80)
Cycle time (s)	−0.11 NS	−0.21 NS	0.40**	0.29 NS	0.29**
Cycle rate (cycles/s)	0.10 NS	0.21 NS	−0.41**	−0.31 NS	−0.31**
Cycle length (m)	0.38*	0.62***	0.86***	0.83***	0.84***
Poling time$_{ABS}$ (s)	−0.54***	−0.52***	−0.24 NS	−0.49***	−0.42***
Poling time$_{REL}$ (%)	−0.32*	−0.31*	−0.52***	−0.63***	−0.56***
Swing time$_{ABS}$ (s)	0.02 NS	−0.07 NS	0.46**	0.43**	0.40***
Swing time$_{REL}$ (%)	0.33*	0.32*	0.53***	0.62***	0.56***
Distance pole-toe PP (m)	0.03 NS	0.31 NS	0.74***	0.28 NS	0.55***
Distance pole-toe PO (m)	−0.01 NS	0.01 NS	0.54***	0.62***	0.54***
PP Poles to vertical (°)	0.01 NS	−0.31 NS	−0.65***	−0.16 NS	−0.48***
PP Tibia to vertical (°)	0.35*	0.13 NS	0.49***	0.59***	0.55***
PP Trunk to vertical (°)	0.01 NS	0.05 NS	−0.40*	0.03 NS	−0.22*
PP Ankle-hip to vertical (°)	0.14 NS	0.26 NS	0.57***	0.44**	0.56***
PP Ankle-shoulder to vertical (°)	0.13 NS	0.27 NS	0.29 NS	0.51***	0.45***
PP Ankle-hand to vertical (°)	−0.01 NS	−0.01 NS	0.18 NS	0.29 NS	0.20 NS
PP Elbow (°)	0.04 NS	−0.06 NS	−0.32*	−0.11 NS	−0.19 NS
PP Hip (°)	−0.18 NS	−0.08 NS	0.45**	−0.09 NS	0.23*
PP Knee (°)	−0.45**	0.02 NS	−0.03 NS	−0.67***	−0.15 NS
PO Poles to vertical (°)	0.22 NS	−0.06 NS	−0.30 NS	0.08 NS	−0.15 NS
PO Tibia to vertical (°)	0.23 NS	−0.23 NS	−0.22 NS	−0.24 NS	−0.21 NS
PO Trunk to vertical (°)	0.19 NS	0.19 NS	−0.19 NS	0.18 NS	0.06 NS
PO Elbow (°)	−0.14 NS	0.43**	0.33*	−0.12 NS	0.12 NS
PO Hip (°)	−0.37*	−0.22 NS	0.34*	−0.16 NS	−0.05 NS
PO Knee (°)	−0.29 NS	0.28 NS	0.25 NS	0.03 NS	0.10 NS

PP, pole plant; PO, pole – off; * = p < 0.05; ** = p < 0.01; *** = p < 0.001, NS = not significant.

Figure 2). The faster skiers were having a more forward lean of the body (greater ankle to hip and ankle to shoulder angle) and more vertically planted poles at PP than the slower skiers, which is in line with earlier research (Smith et al., 1996; Stöggl & Holmberg, 2011, 2016; Zoppirolli et al., 2015). These two findings indicate that the faster skiers try to cover more distance in the forward direction and to use more of their body weight on their poles at PP and possibly therefore create higher poling forces during the poling phase. Although, most of these differences seems to be a result of the higher DP velocity of the male/faster skiers. The only differences remaining for the pole and body angles, when counting for the DP velocity (ANCOVA) was the hip angles at PP (sexes) and PO (sexes and performance level). The difference in distance between pole and toecap at PO was not affected by the DP velocity. We could also find a correlation between the distance from the toecap to the pole tip at PP and DP velocity which is in line with previous studies (Stöggl & Holmberg, 2011, 2016).

There were no differences between the faster and slower skiers in the trunk, hip, knee or tibia angles at PP, even though earlier studies have shown that better skiers are having a larger knee and/or hip angle at PP (Lindinger & Holmberg, 2011; Zoppirolli et al., 2015). This indicates that the skiers in the present study may have individual ways to create a more forward body lean at PP, which also is shown in the relatively high standard deviation in these parameters. When having a more forward body lean at PP, the skier is shifting his/her centre of mass in front of the pivot point of the binding and therefore creates a higher pressure on the poles by greater application of the body weight (Stöggl & Holmberg, 2016; Zoppirolli et al., 2015).

Cycle characteristics

Although the DP velocity was higher for the faster skiers compared with the slower skiers, no difference was found for CL or CR when comparing the two groups, which is in line with Smith et al. (1996) and Sandbakk et al. (2016). Although, when including the DP velocity as covariate (ANCOVA), faster skiers had a higher CR and CL compared to the slower group. There were substantial individual variations in CL and CR, which indicates that the best skiers are employing a high CL and/or CR to create a high DP velocity. Earlier studies have shown that there seems to be an "optimal" CR of 1.2 Hz and CL of 7.5 m during treadmill roller skiing at 1.5° inclination (Stöggl & Müller, 2009). In the present study, the mean values across the entire group were slightly lower for CR (0.96 Hz) and slightly shorter for CL (7.01 m) compared with the "optimal" values from Stöggl and Müller (2009), which may be a result of that the DP section was performed during a real competition outside on snow compared with treadmill roller skiing indoor. The only variable for cycle characteristics that differed between the faster and slower skiers was absolute PT, which can be attributed to the higher skiing speeds in the faster group (Lindinger et al., 2009; Stöggl & Holmberg, 2011, 2016). Despite the lack of differences between the performance groups with respect to CL, we could see a correlation between DP velocity and CL for the group in total (also after the partial correlation analysis with sex as confounder), which is in line with earlier studies (Smith et al., 1996; Stöggl & Holmberg, 2011; Stöggl et al., 2007; Stöggl, Müller, Ainegren, & Holmberg, 2011). Although, when taking the DP velocity into consideration, a difference occurred between the faster and slower skiers regarding CT, CR and CL.

The results also show that there are marked sex differences with respect to cycle characteristics (CT, CR, CL, relative PT, absolute and relative ST) and these differences remained also after correction for the DP velocity. In line with findings of Sandbakk et al. (2014) the greatest difference in cycle characteristics between the sexes were found in CL (23% shorter for female skiers), which is comparable with the difference of 24% found in the present study. The female skiers had a shorter CT and absolute ST, while the absolute PT was similar for the sexes. The great potential for female XC skiers with respect to the DP technique and DP capacity was recently shown by Stöggl et al. (2018).

Conclusion

This study shows the importance of DP velocity for overall classical performance in a 10/15 km race. In the present study, faster skiers were having a more pronounced forward body lean and more vertically placed poles at PP compared to the slower skiers, although this seems to be a result of the higher DP velocity. 82% of the participants were using heel-raise and the timing of the ending of the heel-raise seems to be important for DP performance, with no difference found for when the heel-raise started. Therefore, it seems to be favourable if the heel-raise lasts longer and ends later during the poling phase. Taken together, the use of heel-raise, more pronounced forward body lean and more vertically placed poles might help the skier to cover more distance in a forward direction with every cycle and to use their body weight in a more beneficial way and therefor produce a higher DP velocity.

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No potential conflict of interest was reported by the authors.

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