European Journal of Applied Physiology (2018) 118:271–281
https://doi.org/10.1007/s00421-017-3767-x

ORIGINAL ARTICLE

Pole lengths influence O_2-cost during double poling in highly trained cross-country skiers

Camilla Høivik Carlsen[1] · **Bjarne Rud**[1] · **Håvard Myklebust**[1] · **Thomas Losnegard**[1]

Received: 11 April 2017 / Accepted: 20 November 2017 / Published online: 1 December 2017

Abstract

Purpose In elite cross-country skiing, double poling is used in different terrain. This study compared O_2-cost and kinematics during double poling with four different pole lengths [self-selected (SS), SS − 5 cm, SS + 5 cm, SS + 10 cm] at Low versus Moderate incline.

Methods Thirteen highly trained male cross-country skiers (mean ± SD 23 ± 3 years; 182 ± 4 cm; 77 ± 6 kg) completed eight submaximal trials with roller skis on a treadmill at two conditions: “Low incline” (1.7°; 4.5 m s^{-1}) and “Moderate incline” (4.5°; 2.5 m s^{-1}) with each of the four pole lengths. O_2-cost and 3D body kinematics were assessed in each trial.

Results In Low incline, SS + 10 cm induced a lower O_2-cost than all the other pole lengths [$P < 0.05$; effect size (ES) 0.5–0.8], whereas no differences were found between the remaining pole lengths ($P > 0.05$; ES 0.2–0.4). In Moderate incline, significant differences between all pole lengths were found for O_2-cost, with SS − 5 cm > SS > SS + 5 cm > SS + 10 cm ($P < 0.05$; ES 0.6–1.8). The relative differences in O_2-cost between SS and the other pole lengths were greater in Moderate incline than Low incline (SS − 5 cm; 1.5%, ES 0.8, SS + 5 cm; 1.3%, ES 1.0, and SS + 10 cm; 1.9%, ES 1.0, all $P < 0.05$). No difference was found in cycle, poling or reposition times between pole lengths. However, at both conditions a smaller total vertical displacement of center of mass was observed with SS + 10 cm compared to the other pole lengths.

Conclusion Increasing pole length from SS − 5 cm to SS + 10 cm during double poling induced lower O_2-cost and this advantage was greater in Moderate compared to Low incline.

Keywords Cross-country skiing · Exercise economy · Equipment · Center of mass · Skiing technique

Abbreviations

ANOVA	Analysis of variance
COM	Center of mass
COM_z	Vertical position of the center of mass
COM_{zmin}	Minimum value of the vertical position of the center of mass
COM_{zmax}	Maximum value of the vertical position of the center of mass
$D_{COM-pole\ plant}$	The shortest distance between COM and the poles at pole plant
DIA	Diagonal stride; skiing technique which propulsive forces are transferred through poles and skies
DP	Double poling; skiing technique which propulsive forces are transferred sorely through the poles
SD	Standard deviation
SS	Self-selected
ES	Effect size
FIS	International Ski Federation
HF_{max}	Maximal heart rate
Low incline	Low gradient uphill
Max	Maximum
Min	Minimum
Moderate incline	Moderate gradient uphill

Communicated by Jean-René Lacour.

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00421-017-3767-x) contains supplementary material, which is available to authorized users.

✉ Thomas Losnegard
thomas.losnegard@nih.no

[1] Department of Physical Performance, Norwegian School of Sport Sciences, Ullevål Stadion, Post Box 4014, 0806 Oslo, Norway

O_2-cost	Oxygen cost
ROM	Range of motion
RPE	Rate of perceived exertion
SS − 5 cm to SS + 10 cm	Increase from SS − 5 cm to SS to SS + 5 cm to SS + 10

Introduction

In classical cross-country skiing, double poling (DP) and diagonal stride (DIA) are the most frequent used sub-techniques in competitions. These sub-techniques are considered as a gearing system (Pellegrini et al. 2013), where DP traditionally was used in flat terrain and DIA preferred in uphills. However, skiers have now developed the technique and upper-body endurance and strength to also use DP during Moderate to steep uphill skiing. These sections are of special importance since ~ 50% of the total race time is spent in uphill terrain and is the major determinant of the overall performance during time trials (Andersson et al. 2010; Bolger et al. 2015; Sandbakk et al. 2016).

Skiing speed depends on several physiological and mechanical factors. One of these factors is the O_2-cost of locomotion, defined as the amount of energy expended per unit of velocity (di Prampero 2003), and there have been reports of a close relationship between O_2-cost and performance in cross-country skiing (Ainegren et al. 2013; Losnegard et al. 2017; Mahood et al. 2001). During DP, propulsive forces are transferred sorely through the poles, suggesting that pole length is an important parameter for O_2-cost and performance (Losnegard et al. 2017). However, previous studies have exclusively investigated the influence of pole length in flat or slightly inclined terrain, i.e., < 2.5° (Hansen and Losnegard 2010; Hoffman et al. 1994; Losnegard et al. 2017; Nilsson et al. 2003, Onasch et al. 2016) and little is known about how pole length influences performance or performance-related mechanisms on steeper inclines.

The chosen pole length is a compromise between the optimal lengths used in different sub-techniques, exemplified by use of longer poles in ski skating (~ 90% of body height) than in classical style (traditionally between 82–85% of body height) (Hansen and Losnegard 2010). The reason for this difference is not clear, but according to anecdotes from the cross-country skiing milieu, the arm movement ("low shoulder") during the reposition phase in DIA restricts the use of longer poles in classical style. However, it has been proposed that longer pole lengths in DP may have a greater advantage in uphill versus flat terrain (Losnegard et al. 2017) and thereby compensate for the possible disadvantages of DP in uphills compared to DIA. Therefore, from season 2016–2017, a temporary rule from the International Ski Federation (FIS) restricts the classical pole length to 83% (including ski boots, equivalent to ~ 85% of lean body height) (FIS 2017). FIS states that "the primary goal of this rule is not to ban double poling, but to add an additional tool to protect classical technique and all its aspects (diagonal, double poling, kick double poling, herringbone) so that competitions in classical technique are fair for everybody" (FIS 2016). However, scientific evidence of the effect of pole length in uphill terrain on performance or performance-related factors is limited.

During uphill DP, movement patterns change substantially compared to flat terrains (Millet et al. 1998; Pellegrini et al. 2013; Stöggl and Holmberg 2016). Skiers demonstrate a smaller hip flexion angle during the entire cycle, while flexion and extension of the knee and ankle joints are more pronounced with a greater range of motion (ROM) in uphill versus flat terrain (Stöggl and Holmberg 2016). In combination, these technical alterations enable the skier to reposition body segments and poles more rapidly for the next pole plant and allow the body mass to be more effectively used for the production of pole force (Holmberg et al. 2005; Stöggl and Holmberg 2016). However, such technical change could increase the moment of force in the knee and ankle joints, and thus require greater force production with subsequent higher energy consumption (Blanpied and Nawoczenski 2010). Recently, Losnegard et al. (2017) demonstrated that when DP with 7.5 cm longer poles in slightly inclined terrain (2.5°), skiers used more extended joints and a smaller ROM in the lower limbs compared to self-selected pole lengths. Since longer poles may cause a more upright working position and reduce the ROM in steeper terrain, longer poles may potentially have a greater impact on skiers' O_2-costs as inclination increases.

Considering the lower O_2-cost induced by longer poles in slightly inclined terrain (Losnegard et al. 2017), together with the increasing use of DP in uphill, the present study investigated how pole length influences the O_2-cost and joint kinematics during DP in two different uphill conditions. The main hypothesis was that longer poles would induce a lower O_2-cost compared to self-selected pole lengths and that this difference would increase with steeper terrain.

Methods

Subjects

Thirteen highly trained male cross-country skiers (mean ± SD 23 ± 3 years; 182 ± 4 cm; 77 ± 6 kg) participated in the study. Their self-selected classic style pole length was 154 ± 3 cm (84 ± 1% of body height). Their maximal oxygen uptake, tested during treadmill running on a separate day, was 73 ± 3 mL kg^{-1} min^{-1} (range 68–77) [for the protocol see (Losnegard et al. 2014)]. The study was conducted according to the Declaration of Helsinki and to the

Norwegian law. All the subjects gave their written informed consent before study participation.

Experimental design

Eight of the 13 subjects had limited experience with roller skis on a treadmill prior to the project, and had therefore one familiarization session before taking part in the main tests. On the testing day, O_2-cost and 3D body kinematics were recorded while roller skiing on the treadmill using DP. After 15 min warm-up (1.5°; 2.5–3 m s^{-1}) at ~60–70% of maximal heart rate (HF_{max}), the subjects completed two submaximal uphill conditions: “Low incline” (1.7° and 4.5 m s^{-1}) and “Moderate incline” (4.5° and 2.5 m s^{-1}). The speeds and inclines at each condition were matched for similar external power and were 199W ± 17 and 206W ± 17 in Low and Moderate incline, respectively. External power was calculated as the sum of the power against gravity and the power against rolling friction (Losnegard et al. 2013). Based on pilot testing, the inclines and speeds were chosen to induce a relevant DP technique and to obtain steady-state oxygen uptake. One condition consisted of four 5-min trials separated by 3-min breaks, one with each pole length. Each condition followed the same order (first: “Low incline”; second: “Moderate incline”), while the four pole lengths were counter-balanced in either increasing pole lengths (SS − 5 cm, SS, SS + 5 cm and SS + 10 cm) or (SS + 10 cm, SS + 5 cm, SS and SS − 5 cm). Pole lengths were 82 ± 1, 84 ± 1, 87 ± 1 and 90 ± 1% of body height, respectively, for SS − 5 cm, SS, SS + 5 cm and SS + 10 cm.

Protocol and measurements

The O_2-cost was determined as the average oxygen uptake (mL kg^{-1} min^{-1}) from 3 to 4.5 min in each trial. Heart rate (beats min^{-1}) was similarly averaged. Because of the O_2-measurement apparatus, the subjects were unable to express their rating of perceived exertion [RPE; (Borg 1982)] during the trial. Therefore, at 4 min into the trial, they were asked to choose their RPE, which they then reported at the end of the trial. Gross efficiency was defined as the ratio between external power output (W) and aerobic energy turnover rate (W) and expressed relatively as a percentage (Losnegard et al. 2014).

Prior to each session, the motion capture system was calibrated following the manufacturer’s guidelines. Anthropometrical measurements of each subject (body height, length of leg, thorax, head plus neck and circumference of chest, right upper arm (proximal), elbow, wrist, thigh (proximal), knee- and ankle joint) were acquired. For construction of the modified 3D kinematic model, 27 reflective markers (spherical, 7 mm) were attached over the bony anatomical landmarks (pelvis, thorax, right upper and lower extremities) (Fig. 1). In addition, two markers were placed on the right pole (lateral aspect), 10 and 100 cm from the grip; two markers were placed on the right roller ski, in front of the rear wheel and behind the front wheel; and two markers were placed on the treadmill (85 cm apart) parallel to the skiing direction.

The 3D kinematics of the body, poles and roller skis were collected by a motion capture system in the last 30 s in each trial. The recording lasted 15 s with a sampling rate of 300 Hz. Before recording, the mouthpiece and sampling tube for the O_2 measurements were removed without stopping the treadmill.

Apparatus

All tests were performed on a treadmill (Rodby, Södertalje, Sweden). Prior, during and after the testing period, inclines and speed were controlled and did not show any changes. All subjects used the same pair of roller skis (Swenor Fibreglass, Swenor, Sarpsborg, Norway) with wheel types 2 (front) and 3 (rear). The roller skis had a friction coefficient of 0.026 μ and did not change during the testing period. The binding system was NNN (Rottefella, Klokkarstua, Norway). The subjects used Swix Triac 1.0 poles (Swix, Lillehammer, Norway) with a tip customized for treadmill roller skiing. Before the tests, the tips were adjusted to provide identical grip and weight.

Oxygen consumption was measured using an automatic ergospirometry system (Oxycon Pro, Jaeger GmbH, Hoechberg, Germany), as evaluated by Foss and Hallén (2005). Heart rate was measured with a Polar V800 (Polar Electro OY, Kempele, Finland). Anthropometrics were measured with a stadiometer (Seca 213, Hamburg, Germany) and measuring tape. Body mass (net mass and with equipment) was measured using a Seca scale (model 708, Hamburg, Germany).

Kinematic data were collected using a 3D motion capture system (ProReflex, Qualisys, Sävedalen, Sweden) with Qualisys Track Manager software (QTM) 2.7 and six cameras (Oqus 4, Qualisys Medical AM, Göteborg, Sweden). The global coordinate system was defined as follows: the incline of the treadmill was set to 0°; the *x*-axis was the longitudinal axis of the treadmill (the direction of motion); the *y*-axis was the side-to-side direction across the treadmill; and the *z*-axis was perpendicular to the ground. Visual 3D (C-motion, Inc., USA) and MATLAB (MathWorks, Inc., Natick, MA, USA) were used for further analysis.

Data analysis

Kinematic raw data were filtered (4th order butterworth lowpass filter, cutoff frequency of 6 Hz) and further processed in Visual3D and MATLAB. A kinematic 3D model of the

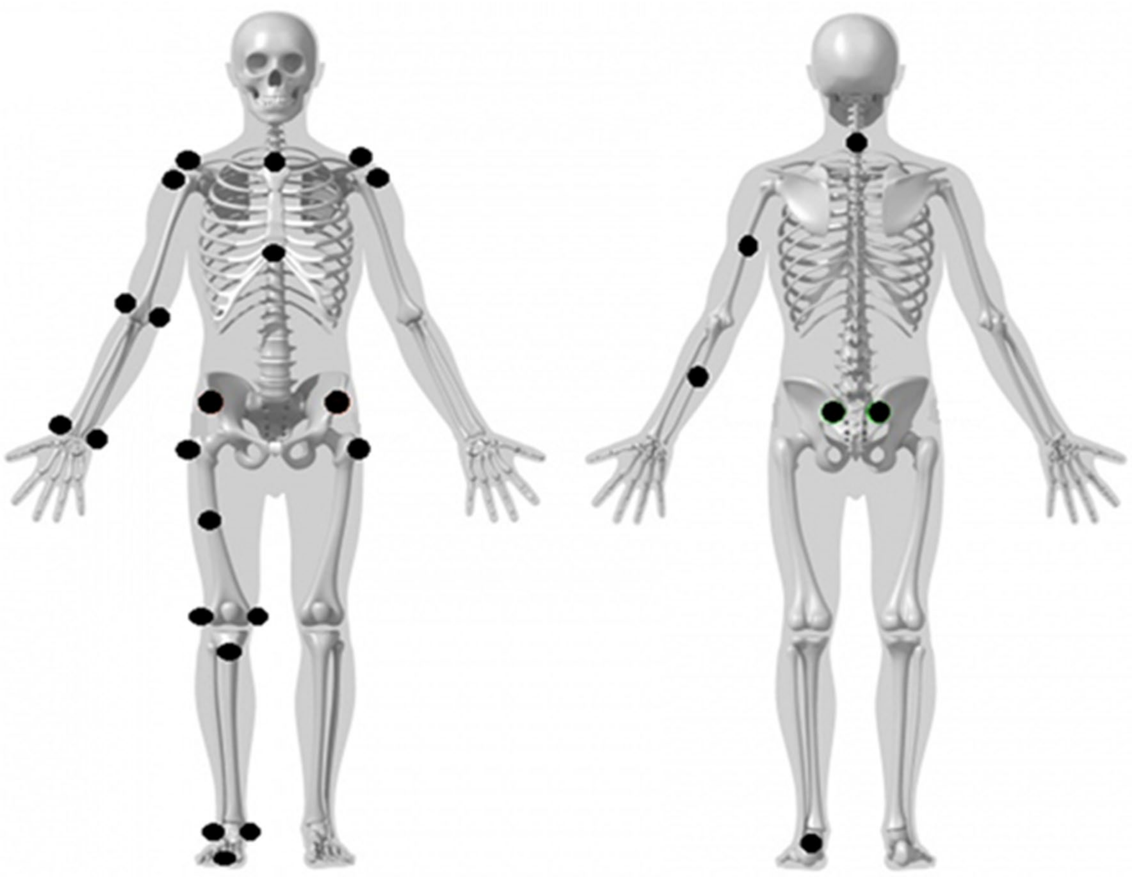

Fig. 1 Illustration of the reflective marker placement. The segments are constructed by the following markers. Foot[a]: lat. malleolus, med. malleolus, calcaneus and 2. metatarsal head. Calf[a]: ant. tibial tuberositas. Thigh[a]: trochanter major[b], ant. thigh, lat. and med. femoral epicondyle. Pelvis: ant. superior iliac spine[b] and pos. superior iliac spine[b]. Truncus: acromion[b], incisura jugularis, xiphoid process and cervical vertebra 7. Upper arm[a]: trochanter major humerus[b], triceps, lat. and med. humerus epicondyle. Forearm[a]: ulna, process styloideus radii and ulnae. [a]Right, [b]right and left, *lat* lateral, *med* medial, *ant* anterior

thorax, pelvis, right arm and leg, together with the right pole and ski was created. Centers of the examined joints were found from the reflective markers (Fig. 1). Cycle time was defined as the time between two pole plants, poling time as the time between pole plant and subsequent pole liftoff, and reposition time as the time between pole liftoff and subsequent pole plant. Pole plant and pole liftoff were determined from the path of the pole markers in Visual 3D, where the pole plant was determined as the maximum forward position in the horizontal plane and pole liftoff was determined as the minimum vertical value in the sagittal plane. The pole angle relative to the treadmill belt plane at pole plant (pole $\text{angle}_{\text{pole plant}}$) and (pole $\text{angle}_{\text{pole liftoff}}$) were calculated in Visual3D. Illustrations of the examined joint angles are provided in Fig. 2.

The vertical position of the center of mass (COM_z) was derived from seven body segments (forearm including the hand, upper arm, trunk and head, pelvis, thigh, leg, and foot), together with two segments for ski and pole. The relative mass of each body segment with respect to the total body mass was calculated based on De Leva (1996). As double poling consists of more or less synchronous movement patterns for the right and left limbs, the 3D model was constructed by extrapolating the right body segment data to also represent the left side segments. The equipment was weighed independently, and the weights of the ski boots were added to the foot segment. Each body segment's COM was calculated with respect to its proximal segmental reference (De Leva 1996), and the COM for the whole body plus equipment was calculated.

For each condition, joint angles and COM_z were calculated from five consecutive cycles. For comparison, each cycle was time normalized using a third-order 101 point interpolation. The average over five consecutive cycles was used for statistical comparison. Joint angles and the vertical position of COM_z for each pole length were compared at pole plant, pole liftoff, and maximum (max) and minimum (min) values during the cycle. The vertical displacement of

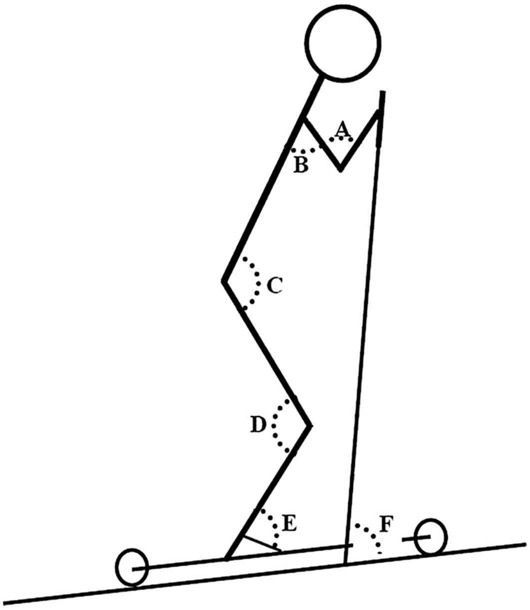

Fig. 2 Illustration of the examined joint and pole angles. A = elbow, B = shoulder (sagittal and frontal plan), C = hip, D = knee, E = ankle and F = pole. For the hip, knee and elbow joints, the maximal extension was defined as 180°. For the ankle joint, 180° represented maximal plantar flexion. For the shoulder joint, the neutral position was defined as 0°. In the sagittal plane, angles > 0° indicated flexion and angles < 0° indicated extension and in the frontal plane full abduction was defined as 180°. For the pole, 0° indicated a right angle between the pole and the horizontal plane

COM_z was calculated from the maximal and minimum values of the vertical position of COM_z ($COM_{zmax} - COM_{zmin}$), regardless of when in the cycle it appeared. Ankle joint coordinates at the pole plant was used as reference point to assess the relative placement of the pole tip. Reported values, $D_{\text{forward-poleplant}}$ and $D_{\text{backwards-poleliftoff}}$, are the distance between this reference point and the pole tip at the pole plant and pole liftoff, respectively. The shortest distance between COM and the poles at the pole plant ($D_{\text{COM-poleplant}}$) were calculated from COM_z and the coordinates of the pole markers.

Statistical analysis

Raw data were checked for normal distribution (Shapiro–Wilks) and presented as mean ± standard deviation (SD) if not otherwise stated. Relative differences between pole length and conditions are presented as mean ± 95% confidence interval (CI). Initially, the main effects of pole length and inclination, as well as the interaction between pole lengths and inclination, were checked with a two-factor within-subject ANOVA (4 × 2 design). If a main effect of pole length was found, one-way ANOVA comparing pole lengths for each of the two inclinations were conducted separately, followed by a Bonferroni post hoc correction for multiple comparisons. If a main effect of inclination was found, paired-samples *T* test was used to compare Low incline and Moderate incline inwardly for one pole length separately.The magnitude of the difference between pole lengths was expressed as standardized mean differences [Cohen's *d* effect size (ES)]. The criteria for interpreting the magnitude of the ES were classified as trivial 0.0–0.2, small 0.2–0.6, moderate 0.6–1.2, large 1.2–2.0 and very large > 2.0 (Hopkins et al. 2009). Statistical calculations were performed using Microsoft Office Excel 2010 (Microsoft, Redmond, USA) and IBM SPSS Statistics 20.0 (International Business Machines (IBM), New York, USA). The level of confidence was set to 95% and a P value ≤ 0.05 was considered statistically significant.

Results

O_2-cost

There was a significant main effect of pole length [$F(3,36) = 31.6$, $P < 0.05$], inclination [$F(1,12) = 186.6$, $P < 0.05$] and of the interaction between pole lengths and inclination [$F(3,36) = 10.9$, $P < 0.05$] on O_2-cost. In Low incline, SS + 10 cm had a lower O_2-cost than SS − 5 cm, SS and SS + 5 cm ($P < 0.05$; ES 0.5–0.8). No significant differences between SS − 5 cm, SS and SS + 5 cm were found ($P > 0.05$; ES 0.2–0.4). In Moderate incline, there was a significant difference between all four pole lengths, with SS + 10 cm inducing the lowest O_2-cost compared to the other pole lengths (SS − 5 cm > SS > SS + 5 cm > SS + 10 cm; $P < 0.05$; ES 0.6–1.8) (Table 1). In Low incline, the relative difference (± CI) in O_2-cost between SS + 10 cm and SS was − 2.1 ± 1.1% ($P < 0.05$; ES 0.6). In Moderate incline, the relative difference were 2.1 ± 1.1% ($P < 0.05$; ES 0.6), − 1.9 ± 0.7% ($P < 0.05$; ES 0.6) and − 4.0 ± 1.0% ($P < 0.05$; ES 1.5), respectively, for SS − 5 cm, SS + 5 cm and SS + 10 cm (Fig. 3). The relative difference in O_2-cost between SS and the pole lengths was greater in Moderate incline compared to Low incline for SS − 5 cm (1.5%, ES 0.8), SS + 5 cm (1.3%, ES 1.0) and SS + 10 cm (1.9%, ES 1.0), all $P < 0.05$. There was no main effect of pole length on heart rate [$F(3,36) = 3.6$, $P > 0.05$], but there was a significant effect of inclination [$F(1,12) = 27.7$, $P < 0.05$] and of the interaction between pole lengths and inclination [$F(3,36) = 6.3$, $P < 0.05$]. The relative difference in heart rate between SS and pole lengths was only significant for SS − 5 cm and was greater in Low incline compared to Moderate incline (− 1.7%, ES 1.3, $P < 0.05$). Pole length [$F(3,36) = 3.3$, $P > 0.05$] and the interaction between pole lengths and inclination [$F(3,36) = 0.4$, $P > 0.05$] had no main effect on RPE, but inclination had a significant effect [$F(1,12) = 24.5$, $P < 0.05$]. The relative difference of

Table 1 Physiological responses (upper part), and temporal and kinematic characteristics (lower part) for all pole lengths in Low and Moderate incline

Variable	Incline	SS – 5 cm	SS	SS + 5 cm	SS + 10 cm
O_2-cost (mL kg^{-1} min^{-1})	Low	46.1 ± 1.5	45.8 ± 1.7	45.5 ± 1.4	44.8 ± 1.6$^{*,'',\delta}$
	Moderate	50.0 ± 2.2	48.9 ± 1.5*	48.0 ± 1.6*	46.9 ± 1.1$^{*,'',\delta}$
Heart rate (beats min^{-1})	Low	149 ± 10	151 ± 9	150 ± 9	148 ± 8
	Moderate	155 ± 11	154 ± 10	153 ± 10	152 ± 10
Gross efficiency (%)	Low	16.2 ± 0.6	16.3 ± 0.7	16.4 ± 0.6*	16.6 ± 0.7*
	Moderate	15.6 ± 0.8	15.9 ± 0.6*	16.2 ± 0.6$^{*,''}$	16.6 ± 0.5$^{*,'',\delta}$
RPE (6–20)	Low	12.6 ± 1.8	12.2 ± 1.8	12.2 ± 1.4	12.3 ± 1.3
	Moderate	13.7 ± 1.6	13.5 ± 1.6	13.3 ± 1.4	13.3 ± 1.2
Cycle time (s)	Low	1.16 ± 0.08	1.19 ± 0.11	1.17 ± 0.09	1.17 ± 0.10
	Moderate	1.09 ± 0.08	1.11 ± 0.14	1.14 ± 0.10	1.13 ± 0.09
Poling time (s)	Low	0.37 ± 0.04	0.38 ± 0.06	0.38 ± 0.06	0.37 ± 0.05
	Moderate	0.49 ± 0.05	0.50 ± 0.05	0.51 ± 0.06	0.51 ± 0.06
Reposition time (s)	Low	0.79 ± 0.06	0.80 ± 0.07	0.79 ± 0.07	0.80 ± 0.08
	Moderate	0.60 ± 0.06	0.61 ± 0.06	0.61 ± 0.05	0.61 ± 0.06
$D_{\text{forward-pole plant}}$ (cm)	Low	52 ± 16	53 ± 19	49 ± 16	45 ± 18$^{*,''}$
	Moderate	33 ± 12	28 ± 15	26 ± 18	24 ± 15*
$D_{\text{backwards-pole liftoff}}$ (cm)	Low	– 112 ± 5	– 118 ± 10*	– 121 ± 10*	– 124 ± 7*
	Moderate	– 90 ± 6	– 97 ± 8*	– 101 ± 10$^{*,''}$	– 103 ± 6*
Pole angle$_{\text{pole plant}}$(°)	Low	81 ± 7	81 ± 8	81 ± 7	81 ± 7
	Moderate	73 ± 5	73 ± 6	74 ± 7	73 ± 6
Pole angle$_{\text{pole liftoff}}$ (°)	Low	29 ± 2	28 ± 2	28 ± 2	28 ± 2
	Moderate	31 ± 3	31 ± 2	31 ± 2	30 ± 3
COM_zdisplacement (cm)	Low	20 ± 2	20 ± 2	19 ± 3*	19 ± 2$^{*,''}$
	Moderate	21 ± 2	20 ± 2*	20 ± 3*	19 ± 2*
$D_{\text{COM-pole plant}}$(cm)	Low	0.45 ± 0.05	0.45 ± 0.05	0.43 ± 0.05	0.42 ± 0.06
	Moderate	0.38 ± 0.03	0.36 ± 0.04	0.35 ± 0.05	0.33 ± 0.03$^{*,''}$

Data are presented as mean ± SD ($n = 13$)

RPE rate of perceived exertion, $D_{forward\text{-}poleplant}andD_{backwards\text{-}poleliftoff}$ *(cm)* distance from the pole tip to the ankle joint, *Pole angle*$_{poleplant}$ *and pole angle*$_{poleliftoff}$ *(°)* pole angle relative to the treadmill belt plane, COM_z the vertical center of mass, $D_{COM\text{-}poleplant}$ *(cm)* the shortest distance between COM and the poles at the pole plant

*Significant difference from SS – 5 cm ($P < 0.05$)

″Significant difference from SS ($P < 0.05$)

$^{\delta}$Significant difference from SS + 5 cm ($P < 0.05$)

RPE between SS and pole lengths was only significant for SS – 5 cm and was greater in Low incline compared to Moderate incline (2.0%, ES 0.4, $P < 0.05$) (Table 1).

Displacement of COM

There was a significant main effect of pole length [$F(3,33) = 16.4$, $P < 0.05$] and of inclination [$F(1,11) = 6.6$, $P < 0.05$] on the total displacement of COM_z. However, no significant interaction was found between pole lengths and inclination [$F(3,33) = 2.1$, $P > 0.05$]. Post hoc analyses showed that SS – 5 cm had the largest total displacement of COM_z and was significantly different from SS + 5 cm and SS + 10 cm in Low incline, and different from all other pole lengths in Moderate incline ($P < 0.05$; ES 0.6–1.0) (Table 1). However, the total displacement of COM_z when pole length increased from SS – 5 cm to SS to SS + 5 cm to SS + 10 cm (SS – 5cm to SS + 10 cm) was almost identical between Low and Moderate incline (Figs. 4, 5; Table 1).

Joint kinematics

There were a significant main effect of pole lengths on hip, knee and ankle angle in both Low and Moderate inclines (all, $P < 0.05$). The hip and knee joints were more extended at the pole plant, pole liftoff, and minimum and maximum angles with SS + 10 cm than with SS + 5 cm, SS or SS – 5 cm in both Low and Moderate incline, but in Moderate incline the knee had the largest extension with SS + 5 cm. During the DP cycle, the ROM for the hip and knee joint decreased with increasing pole length from SS – 5 cm to SS + 10 cm in both Low and Moderate

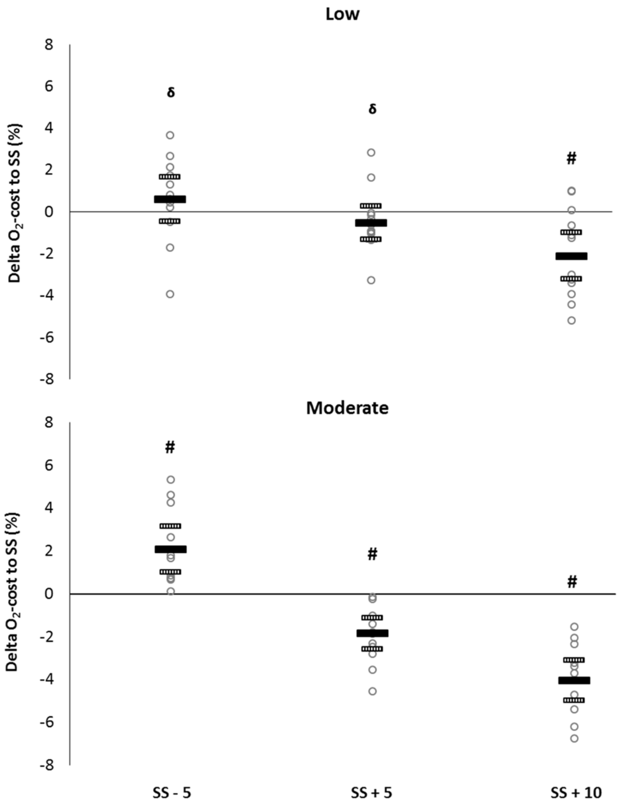

Fig. 3 Individual differences in O_2-cost relative to self-selected pole length in Low incline (1.7°; upper panel) and Moderate incline (4.5°; lower panel). Data are presented as individual (gray circles) and mean (black line) with 95% CI (dotted line). $^{\delta}$Significant difference from SS + 10 cm ($P < 0.05$). $^{\#}$Significant difference between all pole lengths ($P < 0.05$)

inclines, but in Moderate incline the knee joint had the smallest ROM with SS + 5 cm (Figs. 4, 6).

There was a significant main effect of pole lengths on shoulder abduction angle at the pole plant in both the Low and Moderate inclines ($P < 0.05$). Shoulder abduction at the pole plant increased with increasing pole length from SS − 5 cm to SS + 10 cm in both Low and Moderate inclines, but there was only a significant difference between SS + 10 cm and SS − 5 cm and SS (both, $P < 0.05$) in the Low incline trials (Fig. 5).

There was a significant main effect of pole lengths on elbow angle at pole plant in Moderate incline ($P < 0.05$), but not in Low incline ($P > 0.05$). Elbow flexion at the pole plant increased with longer pole length, but there was only a significant difference between SS + 10 cm and SS − 5 cm, and SS + 5 cm and SS − 5 cm ($P < 0.05$) (Fig. 6).

There was a non-significant main effect of pole lengths on pole angle relative to the horizontal in both Low and Moderate inclines ($P > 0.05$). However, there was a significant main effect of pole length on the distance between the pole tip and the ankle joint at the pole plant ($P < 0.05$) for both Low and Moderate inclines. SS + 10 cm showed a pole plant closer to the ankle joint compared to SS − 5 cm and SS in Low incline ($P < 0.05$) and SS − 5 cm in Moderate incline ($P < 0.05$) (Table 1). Thus, the distance between the COM and the pole ($D_{\text{COM-poleplant}}$) was less with SS + 10 cm in Moderate incline ($P < 0.05$). The relative difference in $D_{\text{COM-poleplant}}$ between SS + 10 cm and SS − 5 cm was greater in Moderate incline compared to Low incline (Table 1).

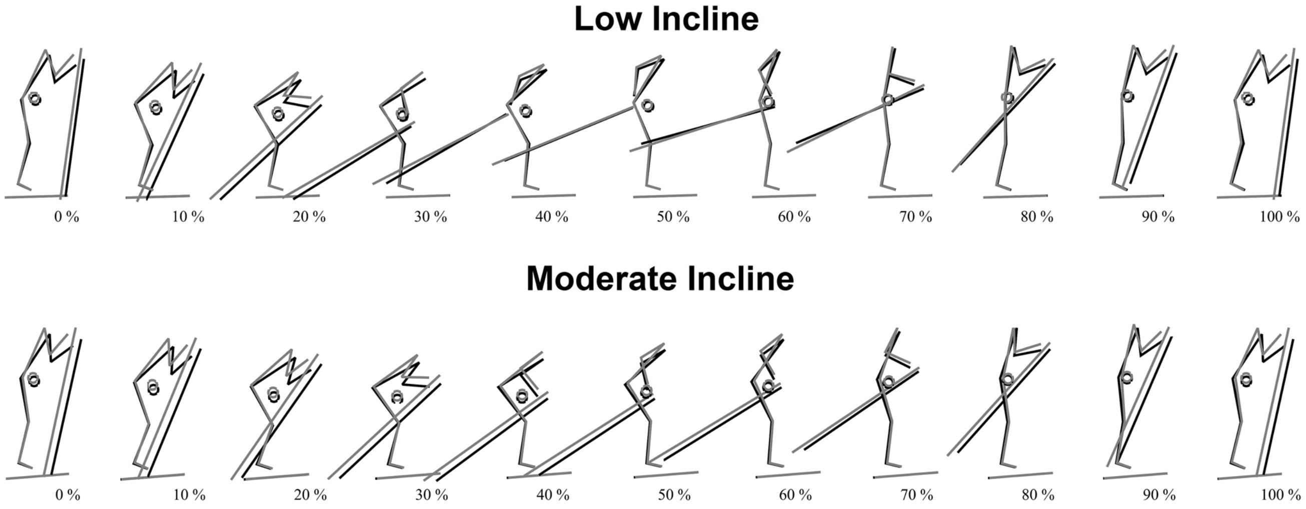

Fig. 4 Kinematic illustration of a full double poling cycle between two pole plants (0–100%). A comparison between SS − 5 cm (black) and SS + 10 cm (grey) in Low incline (upper panel) and SS − 5 cm (black) and SS + 10 cm (grey) in Moderate incline (lower panel). Circles indicate the center of mass. Data are mean values, $n = 13$. For video animation of the above-mentioned comparisons see Online Resources 1 and 2

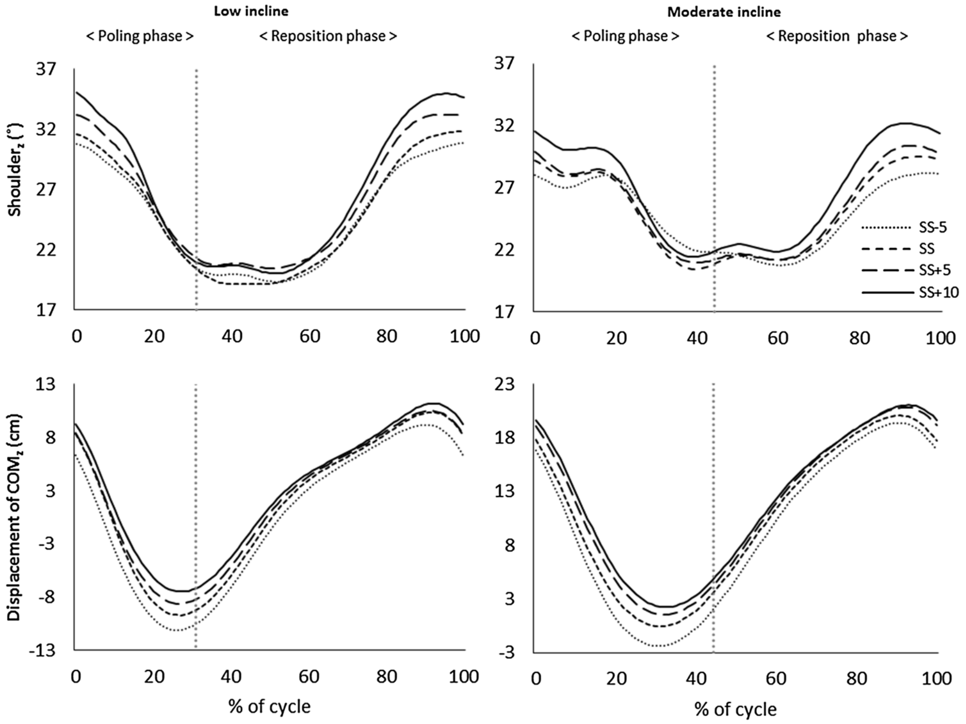

Fig. 5 Shoulder abduction angle (°) (upper panel) and vertical displacement of COM$_z$ (cm) (bottom panel) during a full cycle in Low incline (1.7°; left) and Moderate incline (4.5°; right) for the range of pole lengths. The cycle starts (0%) and ends (100%) at the pole plant, and is divided into the poling and reposition phases (vertical dotted line). Data are mean values, $n = 13$

No significant main effects of pole length on cycle time, poling time or reposition time were found in either Low or Moderate incline ($F_{3,36} = 0.6–2.1$, $P > 0.05$); however, the poling and reposition times for each pole length showed large differences when Low and Moderate inclines were compared (all, $P < 0.05$) (Table 1).

Discussion

This study investigated how pole length affects O$_2$-cost and joint kinematics during DP while treadmill roller skiing in two different uphill conditions. The main findings were that increasing pole length from SS − 5 cm to SS + 10 cm (I) induced a lower O$_2$-cost, (II) with a greater advantage in Moderate incline compared to Low incline and (III) resulted in a more upright posture with reduced total displacement of COM$_z$ during the DP cycle.

The study demonstrated the relationship between pole length and O$_2$-cost, showing that longer poles induced a lower O$_2$-cost compared with shorter and self-selected pole lengths. These results are in accordance with Losnegard et al. (2017) and Onasch et al. (2016), and imply that a pole length up to at least ~ 90% of body height reduces the O$_2$-cost during DP on a treadmill. Notably, these studies have exclusively tested male skiers, and the influence of pole length on O$_2$-cost during DP for female skiers is currently not known.

In Low incline, the O$_2$-cost was 2% lower with SS + 10 cm compared to SS, while in Moderate incline a 4% difference was found. Together with the findings from Losnegard et al. (2017), where a 2.5% lower O$_2$-cost with SS + 7.5 cm compared to SS was found at 2.5°, the present data suggest that the advantage of longer poles increases with the steepness of the incline. Considering that ~ 50% of total race time is spent in the uphill terrain (Andersson et al. 2010; Bolger et al. 2015), and that uphill performance correlates most strongly with overall performance (Sandbakk et al. 2016), the choice of pole length could potentially have a significant impact on cross-country skiers' performance. However, whether our findings can be transferred to snow conditions needs to be examined, in addition to the effects of skiing at high speeds, which are not well documented. These aspects are presently the subject of debate, since FIS (FIS 2017) recently introduced a restriction on pole lengths longer than 83% of body height (including ski boots) in classic-style skiing competitions.

The flexion–extension pattern in the lower limbs was independent of pole length (Fig. 6), but longer poles resulted in a more upright posture caused by more extended ankle, knee and hip joints, with the hip as the most pronounced extension compared to the knee and ankle joints (Fig. 4). Consequently, the total displacement of COM$_z$ was reduced with longer poles. Taken together with previous results (Losnegard et al. 2017), it seems that the reduced overall displacement of COM$_z$ contributes to reducing the O$_2$-cost during DP. However, the relative difference in COM$_z$

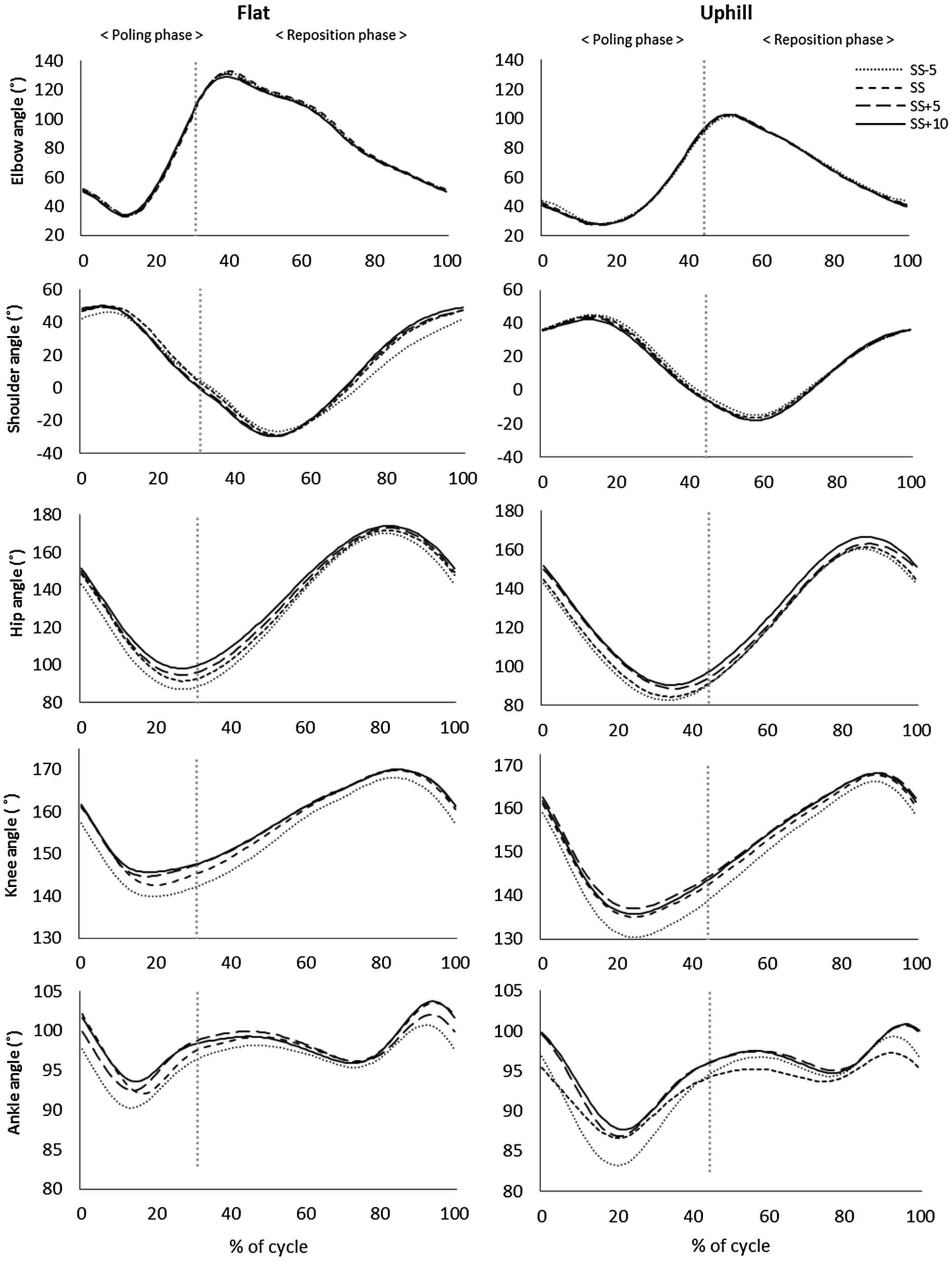

Fig. 6 Elbow, shoulder (flexion/extension), hip, knee and ankle angles (°) during a full cycle in Low incline (1.7°; left) and Moderate incline (4.5°; right) for the range of pole lengths. The cycle starts (0%) and ends (100%) at the pole plant, and is divided into poling and reposition phases (vertical dotted line). Data are mean values, *n* = 13

displacement from SS − 5 cm to SS + 10 cm in Low and Moderate inclines was almost identical (Table 1), suggesting that COM_z displacement alone does not explain why longer poles reduced the O_2-cost more in Moderate incline compared to Low incline. In addition, the present study was conducted on an indoor roller ski treadmill with no aerodynamic drag. Hence, the potential negative effects of the more upright posture on drag forces with longer poles should be considered, particularly at high skiing speeds, when transferring the results to outdoor skiing.

In general, as the steepness of the uphill increases, the amount of work against gravity will also increase. To maintain the same external power, the speed must be reduced and, subsequently, poling time will increase (Losnegard et al. 2017; Stöggl et al. 2011). The poling time affects the muscle contraction time, which according to Hill's law (Hill 1938) influences the effectiveness of muscle contractions.

Therefore, the difference in O_2-cost between pole lengths in Low incline versus Moderate incline could be influenced by the different speeds. However, Losnegard et al. (2017) did not find a statistical interaction between the pole length and speed on O_2-cost within a range of speeds from 3.0 to 4.0 m s^{-1}. The speeds in the present study were only slightly outside this range (2.5 and 4.5 m s^{-1}), and we believe that the difference in O_2-cost between pole lengths in Low incline compared to Moderate incline cannot fully be explained by the differences in speed in Low and Moderate inclines.

During DP, increasing pole length from SS − 5 cm to SS + 10 cm caused a more upright working position due to reduced flexion in the hip before pole plant in both Low and Moderate inclines. This technical alteration reduced the distance between the COM and the poles ($D_{\text{COM-poleplant}}$), and led to a pole plant closer to the ankle joints in both Low and Moderate inclines (Table 1). Interestingly, as for O_2-cost, the difference in $D_{\text{COM-poleplant}}$ between SS − 5 cm and SS + 10 cm was more pronounced in Moderate incline compared to Low incline. This could cause a smaller external moment arm and torque in the working joints and further result in a better working posture, so the same amount of work would be maintained with a lower O_2-cost. Further, DP in different terrains demands clear differences in movement patterns to overcome the external force. With increasing speed during DP in flat terrain, a short poling time is a limiting factor and emphasizes the need for high peak forces generated during a short period of time (Holmberg et al. 2005; Stöggl and Holmberg 2011, 2016; Stöggl et al. 2011). Elite skiers with higher impulse of resultant and horizontal pole force and longer time to peak pole force showed a distinct "pre-preparation" approach with a more forward pole plant (Stöggl and Holmberg 2011), and thus increased $D_{\text{COM-poleplant}}$ to gain sufficient time to provoke a pre-activation of muscles before peak pole forces occur. Unpublished data from our laboratory indicates that pole lengths 90% of body height are not more beneficial at high speeds (8–10 m s^{-1}) compared to self-selected poles (84% of body height), which could, to some extent, be related to the mechanisms mentioned above. As poling time does not seem like a limiting factor in uphill skiing, but rather work against gravity and the ability to use the lowered COM, potentially with a small $D_{\text{COM-poleplant,}}$ could together with the above-mentioned explain some of the greater effect on O_2-cost of increased pole length in Moderate incline compared to Low incline. However, future studies should include kinetic measurements to investigate these assumptions.

A novel finding from the present study was that the shoulders became more abducted at the pole plant in both Low and Moderate incline roller skiing when pole length increased. More abducted shoulders together with smaller elbow angles (Figs. 5, 6) have previously been characterized as a "wide elbow" DP strategy, which is described by specific pole force and muscle activity characteristics directly correlated to DP velocity (Holmberg et al. 2005). Hence, together with more extended ankle, knee and hip joints, more abducted shoulders resulting from longer pole lengths could be a strategy for DP economy enhancement.

Conclusion

Increasing pole length from SS − 5 cm to SS + 10 cm during DP on a treadmill induced lower O_2-cost and total vertical displacement of COM_z, and the advantage of longer poles was greater in Moderate incline compared to Low incline conditions. The present study demonstrated how a change in pole length influences the O_2-cost and kinematic of DP. Whether our findings also occur on snow and if pole lengths influence the overall performance need to be further elucidated. Our findings correspond with the temporary rule from FIS, which restricts the pole length to be longer than 83% of the body height in an attempt to reduce the use of DP during uphills in classic cross-country ski races.

Acknowledgements The authors would like to express their thanks to the participants for their enthusiasm and cooperation during the study. Further, the authors thank Øyvind Gløersen for the data analyses.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Ainegren M, Carlsson P, Tinnsten M, Laaksonen M (2013) Skiing economy and efficiency in recreational and elite cross-country skiers. J Strength Cond Res 27(5):1239–1252

Andersson E, Supej M, Sandbakk Ø, Sperlich B, Stöggl T, Holmberg HC (2010) Analysis of sprint cross-country skiing using a differential global navigation satellite system. Eur J Appl Physiol 110(3):585–595

Blanpied PR, Nawoczenski P (2010) Biomechanical principles. In: Neumann DA (ed) Kinesiology of the musculoskeletal system: foundations for rehabilitation, 2nd edn. Mosby, St. Louis, pp 77–114

Bolger C, Kochbach J, Hegge AM, Sandbakk Ø (2015) Speed and heart rate profiles in skate and classical cross-country skiing competitions. Int J Sports Physiol Perform 10(7):873–880

Borg G (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exer 14(5):377–381

De Leva P (1996) Adjustment to Zatsiorsky–Seluyanov's segment inertia parameters. J Biomech 29(9):1223–1230

di Prampero PE (2003) Factors limiting maximal performance in humans. Eur J Appl Physiol 90(3–4):420–429

Foss Ø, Hallén J (2005) Validity and stability of a computerized metabolic system with mixing chamber. Int J Sports Med 26(7):569–575

Hansen E, Losnegard T (2010) Pole length affects cross-country skiers' performance in an 80-m double poling trial performed on snow from standing start. Sports Eng 12(4):171–178

Hill AV (1938) The heat of shortening and the dynamic constants of muscle. Proc R Soc Lond Ser B 126(843):136–195

Hoffman M, Clifford P, Watts P, Drobish K, Gibbons T, Newbury V, Sulentic JE, Mittelstadt S, O'Hagan K (1994) Physiological comparison of uphill roller skiing: diagonal stride versus double pole. Med Sci Sports Exerc 26(10):1284–1289

Holmberg HC, Lindinger S, Stöggl T, Eitzlmair E, Müller E (2005) Biomechanical analysis of double poling in elite cross-country skiers. Med Sci Sports Exerc 37(5):807–818

Hopkins WG, Marshall SW, Batterham AM, Hanin J (2009) Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc 41(1):3–12

International Ski Federation (FIS) (2017) The international ski competition rules (ICR). Book II. Cross-country. http://www.fis-ski.com/mm/Document/documentlibrary/NordicCombined/03/19/10/ICR_NC_2016-17_clean_English.pdf. Cited 2017 June

International Ski Federation (FIS) (2016) Cross Country World Cup, News and Multimedia. Q&A maximum classic tecnique poles. http://www.fis-ski.com/cross-country/news-multimedia/news/article=maximum-classic-technique-poles.html. Cited 2017 June

Losnegard T, Myklebust H, Spencer M, Hallén J (2013) Seasonal variations in VO_{2max}, O_2-cost, O_2-deficit and performance in elite cross-country skiers. J Strength Cond Res 27(7):1780–1790

Losnegard T, Schäfer D, Hallén J (2014) Exercise economy in skiing and running. Front Physiol. https://doi.org/10.3389/fphys.2014.00005

Losnegard T, Myklebust H, Skattebo Ø, Stadheim HK, Sandbakk Ø, Hallén J (2017) The influence of pole length on performance, O_2-cost and kinematics in double poling. Int J Sports Physiol Perform 12(2):211–217

Mahood N, Kenefick R, Kertzer R, Quinn T (2001) Physiological determinants of cross-country ski racing performance. Sci Sports Exerc 33(8):1379–1384

Millet G, Hoffman M, Candau R, Clifford P (1998) Poling forces during roller skiing: effects of grade. Med Sci Sports Exerc 30(11):1637–1644

Nilsson J, Jakobsen V, Tveit P, Eikrehagen O (2003) Pole length and ground reaction forces during maximal double poling in skiing. Sports Biomech 2:227–236

Onasch F, Killick A, Herzog W (2016) Is there an optimal length for double poling in cross country skiing? J Appl Biomech. https://doi.org/10.1123/jab.2016-0071

Pellegrini B, Zoppirolli C, Bortolan L, Holmberg H, Zamparo P, Schena F (2013) Biomechanical and energetic determinants of technique selection in classical cross-country skiing. Hum Mov Sci 32(6):1415–1429

Sandbakk Ø, Losnegard T, Skattebo Ø, Hegge A, Tønnesen E, Kocbach J (2016) Analysis of classical time-trial performance and technique-specific physiological determinants in elite female cross-country skiers. Front Physiol. https://doi.org/10.3389/fphys.2016.00326

Stöggl T, Holmberg HC (2011) Force interaction and 3D pole movement in double poling. Scand J Med Sci Sports 21(6):393–404

Stöggl T, Holmberg HC (2016) Double-poling biomechanics of elite cross-country skiers: flat versus uphill terrain. Med Sci Sports Exerc 48(8):1580–1589

Stöggl T, Müller E, Ainegren M, Holmberg HC (2011) General strength and kinetics: fundamental to sprinting faster in cross country skiing? Scand J Med Sci Sports 21(6):791–803