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ORIGINAL PAPER

Effects of speed and incline on double-poling biomechanics

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Abstract

This study investigated the independent and combined effects of incline and speed on the kinetics and cycle characteristics of double poling. Seventeen trained male cross-country skiers completed a maximum speed, a maximum incline, and a constant-power-output test on a motorized treadmill. Axial pole force was measured throughout all tests using ski poles equipped with force sensors. The results indicated that the proportion of propulsive pole force relative to axial pole force (i.e., the pole force ratio) decreased linearly with increasing speed, which was explained by declining poling time. Contrarily, the pole force ratio and poling time barely changed by increasing incline; however, considerable inter-individual variation emerged in the former. A large proportion of variables describing cycle characteristics and poling kinetics differed significantly between the final completed stages of the maximum speed and maximum incline tests. Additionally, participants' performance in these tests showed a moderate correlation ($r = 0.50$, $P = 0.04$). Both pole forces and poling impulse, as well as the pole force ratio, showed significant variation during the constant-power-output test, suggesting that, in cross-country skiing, external power output alone is insufficient to accurately capture the magnitude of effort, unless speed and inclination are also considered. The present study highlights the complexity of double-poling biomechanics and underscores the need for further research into physiology- and efficiency-related implications. Finally, it provides practical perspectives for enhancing sprint performance in cross-country skiing through targeted training sessions.

Keywords Cycle characteristics · Force measurement · Poling kinetics · Power output · Sports performance · Sports technology · Training load

1 Introduction

Double poling is one of the fundamental movement patterns, often referred to as sub-techniques, within classical cross-country skiing [1]. It is typically used at relatively high speeds ($\sim 12 - 40$ km/h) on flat terrain, or moderate inclines [2–5]. In recent years, double-poling performance has become increasingly important, and in some long-distance cross-country ski races, such as the Vasaloppet and the Birkebeinerrennet, it is now the exclusively used sub-technique [6, 7].

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In the double-poling sub-technique, propulsion is generated through the skier's poles, indicating an enhanced reliance on the upper-body musculature compared to other sub-techniques [8, 9]. Nevertheless, double poling is not solely reliant on upper-body power production; it also activates lower-body muscles that stabilize the body and counteract the upper body's flexion, as demonstrated by surface electromyography [8]. Moreover, Danielsen and colleagues [10] demonstrated that approximately one-third of the total propulsive power is generated through the use of trunk and leg muscles at a moderate incline, with this contribution increasing at steeper inclines.

Studies on the cycle characteristics and kinetics of double poling have shown that as the speed of travel increases, poling frequency (i.e., cycle rate) and pole force also increase [11, 12]. In contrast, absolute poling time, recovery time (i.e., reposition time or swing time), and time to peak pole force have been shown to decrease. It was also found that steeper slopes increase pole force, poling impulse, cycle rate (CR), time to peak pole force and the pole-off angle [10,

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11, 13, 14]. This results in decreasing cycle length (i.e., the travelled distance during a complete poling cycle), swing time, impact pole force and the pole-plant angle.

One study has investigated the combined effect of speed and incline during constant power output conditions; however, this investigation included only two different incline conditions (i.e., 5% and 12% inclines). The study by Danielsen et al. revealed significant interaction effects of speed and incline for mean and peak pole power, peak pole force, pole-off angle and perpendicular center of mass displacement [12].

Stöggl and Holmberg defined the pole force “effectiveness index” as the ratio of mean propulsive force to mean axial pole force, which was assessed using strain gauge force transducers and motion capture analysis [11]. They found that the "effectiveness index" increased from $\sim 55\%$ to $\sim 65\%$ at a 7° incline compared to a 1° incline, while their results suggested that the "effectiveness index" was relatively invariant to an altered speed.

Although research has demonstrated a positive correlation between upper-body power and maximum speed in double poling within a homogenous sample of elite cross-country skiers [15], the ability to reach a high maximum speed is primarily constrained by the brief available duration (i.e., poling time) for applying substantial forces through the ski poles. As Stöggl et al. [16] concluded, the key to a high maximum speed lies in the transferability of general strength and power to speed production, which requires high levels of technical and coordination skills. This underscores the need for a deeper understanding of double-poling biomechanics to optimize training strategies, particularly for the development of maximum speed and sprint performance.

This study aimed to examine the independent and combined effects of speed and incline on the kinetics and cycle characteristics of double poling. First, it was hypothesized that double-poling at high speeds imposes fundamentally different kinetic demands than at steep inclines. In principle, a high maximum speed capacity at low gradients would not necessarily translate into a high maximum power output capacity at steeper gradients and vice versa. It was further hypothesized that external power output in cross-country skiing cannot be meaningfully interpreted without considering speed and incline. Finally, it was hypothesized that maximum skiing velocity is primarily constrained by the skier’s ability to maintain sufficient propulsive force despite progressively shortening poling time throughout the acceleration phase.

2 Methods

All participants performed three different roller-ski tests on a motor-driven treadmill in the double-poling sub-technique: a maximum speed test, a maximum incline test, and a 10-minute constant-power-output test across various incline conditions (ranging from 1° to 7°) with corresponding variations in speed. The intensity in this latter test was determined relative to the participants’ maximum speed. The three tests together allowed for the investigation of double-poling biomechanics under conditions of constant speed, propulsive force, and power output, respectively. Cycle characteristics and poling kinetics were recorded during all tests using load-cell-equipped ski poles and analysed for differences between tests, test stages and participants.

2.1 Participants

Seventeen trained male cross-country skiers (body mass, 78.3 ± 9.4 kg; body height, 182 ± 7 cm; age, 30 ± 13 years) volunteered for the study. All were familiar with treadmill roller-ski training and testing. The study was conducted according to the Declaration of Helsinki. The study was pre-approved by the Swedish Ethical Review Board (2023-03470-01), and all athletes provided their written informed consent to participate in the study.

2.2 Testing procedure

The participants completed three different treadmill roller-ski tests in the double-poling sub-technique: 1) a maximum speed test, 2) a maximum incline test and 3) a 10-minute constant-power-output test, all performed on the same laboratory visit. The maximum speed test was conducted according to the methodological principles developed by Stöggl et al. [17]. It was performed at a constant inclination of 3° beginning with a 20-second initial stage at 12 km/h. After this stage, the treadmill speed increased by 1 km/h every 6 s until the participant could no longer maintain the pace. The test was terminated when the roller skis’ front wheels dropped behind the treadmill belt’s midpoint (i.e., 1.75 m behind the front roller). The participants wore a safety harness around their waist attached to a rope during all tests. The maximum speed (v_{max}) was defined to account for each commenced stage of the maximum speed test as:

$$v_{max} = \frac{t}{t_{incr}} \cdot v_{incr} + v_0, \tag{1}$$

where is the test duration, $t_{incr} = 6$ s, and $v_0 = 12$ km/h is the initial treadmill speed.

Analogous to the v_{max} test, a maximum incline test was defined and utilized in the study. This test was performed at a constant speed of 12 km/h and an initial incline of 4°. Following the 20-second initial stage, the treadmill incline increased by 0.5° every 6 s until the participant could not maintain the treadmill speed. The maximum incline (α_{max}) was defined as:

$$\alpha_{max} = \frac{t}{t_{incr}} \cdot \alpha_{incr} + \alpha_0, \tag{2}$$

where $\alpha_0 = 4°$ and $\alpha_{incr} = 0.5°$.

Subsequently, all participants completed a 10-min constant-power-output (CPO) test including ten different incline-speed combinations (i.e., one minute per stage). The intensity for this test was prescribed individually based on the participant's maximum power output (P_{max}) corresponding to their v_{max}. Power output on the treadmill was calculated as the sum of power against friction and gravity [11, 18], thus:

$$P_{max} = mg(\mu_r \cos(\alpha) + \sin(\alpha))\, v_{max}, \tag{3}$$

where m is the skier's body mass, g is the gravitational acceleration (9.81 $\mathrm{m/s^2}$) and μ_r is the rolling resistance coefficient. Power output in the CPO test was prescribed as $0.5 \cdot P_{max}$ based on the authors' experience and pilot testing. To make speed shifts more even during the CPO tests, the incline for the stage of the test (α_i) was defined using logarithmic increments between 1° and 7° as:

$$\alpha_i = 10^{\log_{10} 1 + \frac{i-1}{9} \cdot (\log_{10} 7 - \log_{10} 1)}. \tag{4}$$

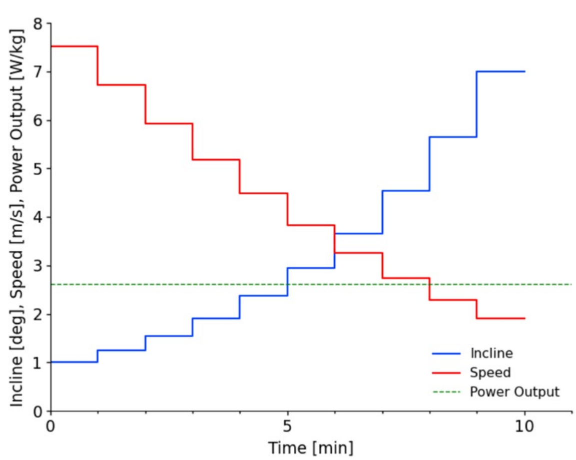

Fig. 1 Illustration of prescribed incline-speed combinations during a 10-min constant-power-output (CPO) test for a participant reaching a maximum speed (v_{max}) of 7.5 m/s (i.e., 27 km/h) in the maximum speed test. The power output (green dashed line) is prescribed based on the participant's power output corresponding to their v_{max}

Treadmill speed (v_i) corresponding to ith stage (Fig. 1) was calculated based on P_{max} and the sum of refraining forces as:

$$v_i = \frac{0.5 \cdot P_{max}}{mg(\mu_r \cos(\alpha_i) + \sin(\alpha_i))}. \tag{5}$$

2.3 Equipment and measurements

All roller-ski tests were performed on a motor-driven treadmill designed for roller skiing (dimensions: 3.5 × 2.5 m; Rodby Innovation AB, Vänge, Sweden). All participants used the same pair of Swenor Alutech classic roller skis (mass: 2100 g/pair, wheels: type 2). The rolling friction coefficient of roller ski wheels (μ_r) was assessed for warmed wheel bearings, based on previously established procedures [18]. According to this measurement, $\mu_r = 0.018$ was used as a constant value in all calculations. During all tests, the participants used a pole-force measurement system, integrating strain-gauge sensors, microprocessors, and wireless communication to enable measurement control over a smartphone application (Skisens Beta Release Generation II, Skisens AB, Gothenburg, Sweden) [19].

The collected axial pole force data were stored at a 100 Hz sampling rate similar to ref. [14], and post-processed in the Skisens software to provide biomechanical variables, for example, poling time, poling impulse, and CR downsampled to a 1 Hz sampling rate. The pole force data collection was the most calibration-sensitive measurement included in our experiments, and consequently, related biomechanical variables (e.g., poling impulse) were dependent on the accuracy of these force measurements. The primary limitation to measurement accuracy was the mechanical friction inside the ski-pole handles, which was shown to influence sensor calibration (see Online Resource). However, it was also demonstrated that repetitive force measurements within a given assembly were reliable following appropriate calibration.

2.4 Biomechanical variables and data analysis

Cycle time was defined as the duration between two subsequent pole plants, swing time as the duration between pole-off and the subsequent pole plant, and relative poling time as the ratio of poling time (i.e., the duration between pole plant and pole-off) to cycle time. Cycle length (CL) was calculated as treadmill speed [m/min] divided by CR [cycles/min]. Poling impulse was computed as the area under the poling time-axial pole force curve. The values presented for axial, propulsive, and perpendicular pole forces, as well as poling impulse, represent the sum of both sides. The pole force ratio (PFR) was defined as the ratio of the sum of the gravitational and frictional forces to the measured axial pole force, as:

$$\mathrm{PFR} = \frac{F_{gravity} + F_{friction}}{F_{axial}} = \frac{mg\left(\sin(\alpha) + \mu_r \cos(\alpha)\right)}{F_{axial}}. \quad (6)$$

The measured axial pole force was plotted against poling time to generate poling time-pole force curves. These curves were utilized to assess differences in poling kinetics between the maximum speed and incline tests, as well as across stages of the CPO test. The analyses focused on the curves' key characteristics, including impact and peak pole forces, their absolute and relative timing, rate of force development (RFD), and the distribution of impulse until and after the peak pole force. Impact pole force was defined as the first local maximum of the time-pole force curve, and time to impact pole force was the corresponding poling time value (i.e., the time from pole plant to the first local maximum). Due to data loss during extraction, the number of participants varies across analyses and is reported where relevant. All data were processed and analyzed using Microsoft Office Excel 2019 (Microsoft Corp., Redmond, WA, USA) and Python v3.12 (Python Software Foundation, Wilmington, DE, USA).

2.5 Statistical analysis

Data normality was assessed using the Shapiro-Wilk test. Differences in cycle characteristics and poling kinetics between the maximum speed and incline tests were assessed using paired t-tests, while the magnitude of effect was assessed using Hedges' g. To quantify correlations between variables, the Pearson product-moment coefficient (r) was calculated. Correlation coefficients were interpreted based on Schober et al. [20]. Regarding the CPO test, the means of measured and calculated mechanical variables were taken over the final 20 s of each stage, tested for differences using one-way repeated-measures ANOVA, and reported together with partial eta-squared (η_p^2) effect sizes. Mauchly's test was used to test the assumption of sphericity, and the Greenhouse-Geisser correction was applied when this assumption was violated. Linear regression models were used to relate PFR and poling time to speed and incline, with model fit assessed by the coefficient of determination (R^2). Statistical analysis was performed in SPSS v29.0 (IBM Corp., Armonk, NY, USA). Results were considered statistically significant at $\alpha = 0.05$. Data are presented as mean ± standard deviation (SD).

3 Results

In the maximum speed test, participants demonstrated $v_{max} = 24.2 \pm 1.5$ km/h, while in the maximum incline test, α_{max} was 8.8° ± 0.7°. These performances corresponded to test durations of 93.1 ± 9.0 seconds and 77.8 ± 8.8 seconds, respectively.

Cycle characteristics and poling kinetics showed considerable differences and negligible to very strong correlations between the two maximum tests, as presented in Table 1. Furthermore, α_{max} demonstrated a moderate correlation with v_{max} ($r = 0.50$, $P = 0.04$).

The PFR showed a linear decline across submaximal speeds (i.e., between 12 and 23 km/h) in the maximum speed test $\mathrm{PFR} = -0.13\,\mathrm{Speed} + 0.75$, $R^2 = 0.99$, $P < 0.001$), which was also representative of individual trends (Fig. 2A). Similarly, poling time typically demonstrated a linear decrease as the treadmill speed was raised ($\text{Poling time} = -9.45\,\mathrm{Speed} + 449.70$, $R^2 = 0.99$, $P < 0.001$; Fig. 2C). Consequently, PFR could be accurately modeled as a function of poling time during the v_{max} tests ($\mathrm{PFR} = 0.001\,\text{Poling time} + 0.153$, $R^2 = 0.99$, $P < 0.001$). No significant correlation was found between the rate of PFR decline across stages (i.e., the slope of individual speed-PFR regression lines) and v_{max} ($r = -0.30$, $P = 0.29$).

Prior to failure in the v_{max} test, CL showed a gradual decline after reaching its peak ($\mathrm{CL_{peak}}$) in all participants. The peak CL showed a strong positive relationship with v_{max} ($v_{max} = 3.04\,\mathrm{CL_{peak}} + 8.16$, $R^2 = 0.81$, $P < 0.001$). It occurred 20.3 ± 4.3 seconds before v_{max} was attained (Fig. 4), corresponding to $\sim 80 - 90\%$ of v_{max}; however, the relative timing of $\mathrm{CL_{peak}}$ (i.e., the ratio of time required to attain to the test duration) was not associated with v_{max} ($P = 0.98$).

Regarding poling kinetics in the maximum speed test, increasing speed was typically associated with higher impact and peak pole forces, a greater rate of force development, and a marked shortening of both poling time and time to peak pole force concerning the v_{max} test (see Fig. 3A, B for examples).

In contrast to the maximum speed test, the PFR barely changed by incline during submaximal stages (i.e., between 4° and 8.5° inclines) in the maximum incline test ($\mathrm{PFR} = 0.003 \times \mathrm{Incline} - 0.54$, $R^2 = 0.46$, $P < 0.001$). Nevertheless, individual trends showed considerable variation, with some participants demonstrating decreasing PFR with increasing incline, while in others, the PFR showed a gradual increase during the test (Fig. 2B). Poling time remained relatively constant at both an average and an individual level ($\text{Poling time} = 1.0 \times \mathrm{Incline} + 354.5$, $R^2 = 0.42$, $P = 0.04$; Fig. 2D). Increased incline resulted

Table 1 Differences and linear correlations between biomechanical variables describing cycle characteristics and poling kinetics during the final completed stages of the maximum speed (v_{max}) and maximum incline (α_{max}) tests

	v_{max} test	α_{max} test	P_{t-test}	g	r	P_{corr}
Treadmill speed [km/h]	23.3 ± 1.6	12.0	–	–	–	–
Treadmill incline [°]	3.0	8.5 ± 0.7	–	–	–	–
External power output [W]	363.8 ± 55.1	$441.7 \pm 69.2^*$	< 0.001	2.94	0.94	< 0.001
Poling impulse [Ns]	95.5 ± 16.1	$180.0 \pm 26.6^*$	< 0.001	3.70	0.59	0.02
Poling time [ms]	224.5 ± 21.0	$355.0 \pm 35.5^*$	< 0.001	4.15	0.55	0.03
Cycle time [ms]	774.3 ± 39.7	766.8 ± 53.5	0.63	−0.12	0.37	0.18
Swing time [ms]	549.8 ± 36.0	$411.9 \pm 36.0^*$	< 0.001	3.03	0.32	0.25
Relative poling time	0.29 ± 0.24	$0.46 \pm 0.03^*$	< 0.001	6.10	0.55	0.03
CR [cycles/min]	77.7 ± 3.9	78.7 ± 5.4	0.52	0.16	0.40	0.14
CL [m]	5.4 ± 1.6	$2.6 \pm 0.2^*$	< 0.001	−1.67	0.04	0.88
Axial pole force [N]	124.9 ± 19.6	$235.0 \pm 31.2^*$	< 0.001	4.39	0.65	0.01
Propulsive pole force [N]	56.1 ± 6.6	$132.5 \pm 20.8^*$	< 0.001	4.84	0.90	< 0.001
Perpendicular pole force [N]	111.1 ± 20.8	$193.4 \pm 28.0^*$	< 0.001	3.78	0.69	0.005
PFR (F_{prop}/F_{axial})	0.46 ± 0.07	$0.57 \pm 0.05^*$	< 0.001	2.19	0.72	0.002
Impact pole force [N]	294.7 ± 104.9	$241.8 \pm 67.9^*$	0.02	−0.96	0.95	< 0.001
Time to impact pole force [ms]	26.3 ± 2.5	25.7 ± 4.8	0.86	−0.06	−0.78	0.02
Relative time to impact pole force	0.12 ± 0.01	$0.08 \pm 0.02^*$	0.02	−1.07	−0.54	0.18
Peak pole force [N]	431.1 ± 72.2	451.4 ± 95.5	0.61	0.14	0.61	0.04
Time to peak pole force [ms]	74.7 ± 11.7	$124.7 \pm 33.3^*$	< 0.001	1.47	0.54	0.07
Relative time to peak pole force	0.33 ± 0.05	0.35 ± 0.09	0.65	0.13	0.48	0.13
$\mathrm{RFD_{impact}}$ [kN/s]	11.4 ± 4.2	9.9 ± 2.9	0.08	−0.65	0.80	0.02
$\mathrm{RFD_{peak}}$ [kN/s]	12.6 ± 5.9	$6.0 \pm 2.8^*$	< 0.01	−1.22	0.59	0.56
Impulse until peak pole force [Ns]	19.3 ± 2.3	$38.0 \pm 14.5^*$	< 0.001	1.53	0.61	0.04
Impulse after peak pole force [Ns]	29.2 ± 5.6	$51.3 \pm 9.6^*$	< 0.001	2.35	0.41	0.19
Relative impulse until peak pole force	0.40 ± 0.03	0.42 ± 0.11	0.55	0.17	−0.12	0.97
Relative impulse after peak pole force	0.60 ± 0.03	0.58 ± 0.11	0.55	−0.17	−0.12	0.97

* Significantly different value compared with the maximum speed test ($P < 0.05$)

P_{t-test}, P-value for paired t-tests; g, Hedges' g effect size; P_{corr}, P-value for linear correlations; r, Pearson correlation coefficient; CR, cycle rate; CL, cycle length; PFR, pole force ratio; F_{prop}, propulsive pole force; F_{axial}, axial pole force; $\mathrm{RFD_{impact}}$, rate of force development of the impact pole force; $\mathrm{RFD_{peak}}$, rate of force development of the peak pole force

in a higher peak pole force and a larger area under the poling time-pole force curve while the overall shape of the curve and the relative timing of the peak pole force were maintained (see Fig. 3C, D for examples).

Power output during the CPO test was 185.2 ± 19.5 W (i.e., 2.43 ± 0.16 W/kg). Throughout this test, the PFR and poling time both showed a nonlinear increase, while a combined effect on the characteristics of the poling time-pole force curve was observed (Table 2).

4 Discussion

This study demonstrated that speed and incline have distinct and independent effects on the kinetics and cycle characteristics of double poling. Increasing speed reduced both the PFR and poling time, while increasing pole forces. An increasing incline elevated pole forces, but typically did not affect the PFR or poling time. When speed and incline were manipulated simultaneously at a constant power output (i.e., decreasing speed while increasing incline), their combined effects resulted in a longer poling time, a greater poling impulse, and a higher PFR, without significantly affecting cycle rate.

4.1 Independent and combined effects of speed and incline

Comparison of the final stages of the maximum speed and maximum incline tests revealed distinct biomechanical demands on the participants, with significant differences in most reported variables. Axial pole force, poling time, and poling impulse were all substantially higher during the last completed stage of the maximum incline test compared

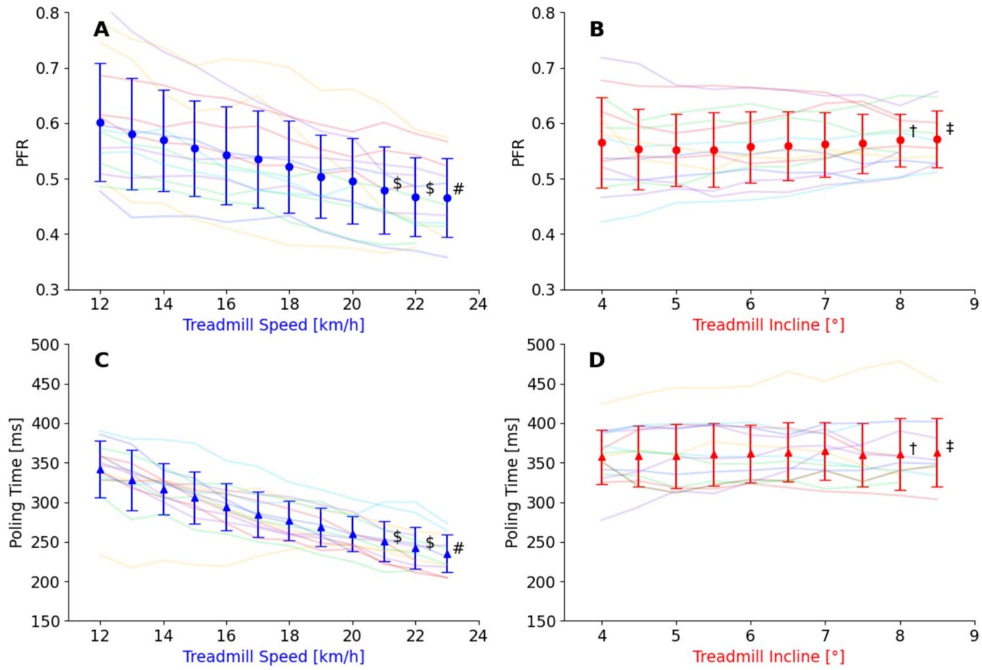

Fig. 2 Effects of speed and incline on the pole force ratio (PFR), defined as the proportion of propulsive pole force relative to the measured axial pole force (panels **A** and **B**), and on poling time (panels **C** and **D**) during double poling at submaximal intensities in the maximum speed test (i.e., constant propulsive force condition) and in the maximum incline test (i.e., constant speed condition), respectively. The maximum speed test was performed at a 3.5° incline, while the maximum incline test was performed at a constant speed of 12 km/h. Only stages in which kinetic data could stabilize were included in the analysis. Maximum speed test data are presented for $n = 16$ participants, while maximum incline test data are presented for $n = 15$ participants, except for the final stages, due to individual differences in performance. Data are presented as $\text{mean} \pm \text{SD}$. The faint lines indicate results from individual participants. $, data from $n = 15$ participants; #, data from $n = 11$ participants; †, data from $n = 12$ participants; ‡, data from $n = 9$ participants

with the maximum speed test (Table 1). In contrast, CR did not differ significantly, suggesting that during maximal-intensity roller skiing, CR may be primarily determined by intrinsic factors, such as anthropometrics, muscle contraction velocity, and pole length, rather than by extrinsic factors such as gradient. The observed moderate correlation between v_{max} and α_{max} ($r = 0.50$, $P = 0.04$) further supports the hypothesis that the two maximum tests imposed fundamentally different biomechanical demands on the participants. Therefore, it was concluded that a high short-duration power output capacity over climbs does not necessarily indicate a high maximum speed capacity on moderate inclines, and vice versa.

Regarding the PFR, previous work by Stöggl and Holmberg [11] reported an 18% higher effectiveness index during uphill compared to flat double poling, albeit under different power output conditions. Our findings show an even greater increase of 29% in the PFR between 1° and 7° (Table 2) in the CPO test. Moreover, our results extend previous findings by revealing the linear decrease in both poling time and the PFR with increasing speed (Fig. 2). Nevertheless, comparisons across studies should be interpreted with caution due to differences in assessment methods. During the maximum incline test, trends in the PFR across stages showed relatively high inter-individual variation, with some participants demonstrating a decrease (~ 0.05), while others maintained or even increased the PFR as the incline rose. This observation is likely explained by two competing effects under increasing incline conditions: greater alignment with the sagittal plane may promote an increased PFR, whereas increasing CR may result in altered pole-off angles [11], thereby suppressing the PFR. Nevertheless, this interpretation remains speculative, as no 3-d kinematic data were collected.

Our results indicate that the increasing incline primarily affected the magnitude of peak pole force (see Fig. 3C, D for examples). However, notable inter-individual differences were observed in the consistency of axial pole force-time curves of two participants with similar performances. In particular, the standard deviation of time to peak pole force during the maximum incline test was higher for Skier B than for Skier A (Fig. 3C, D) reflected by a leftward shift in the timing of the peak pole force at steeper inclines (Fig. 3D). This shift may impair performance, as it suggests that a greater portion of the axial pole force was applied when the poles were positioned more vertically relative to the ground, which could potentially reduce the mechanical efficiency of propulsion.

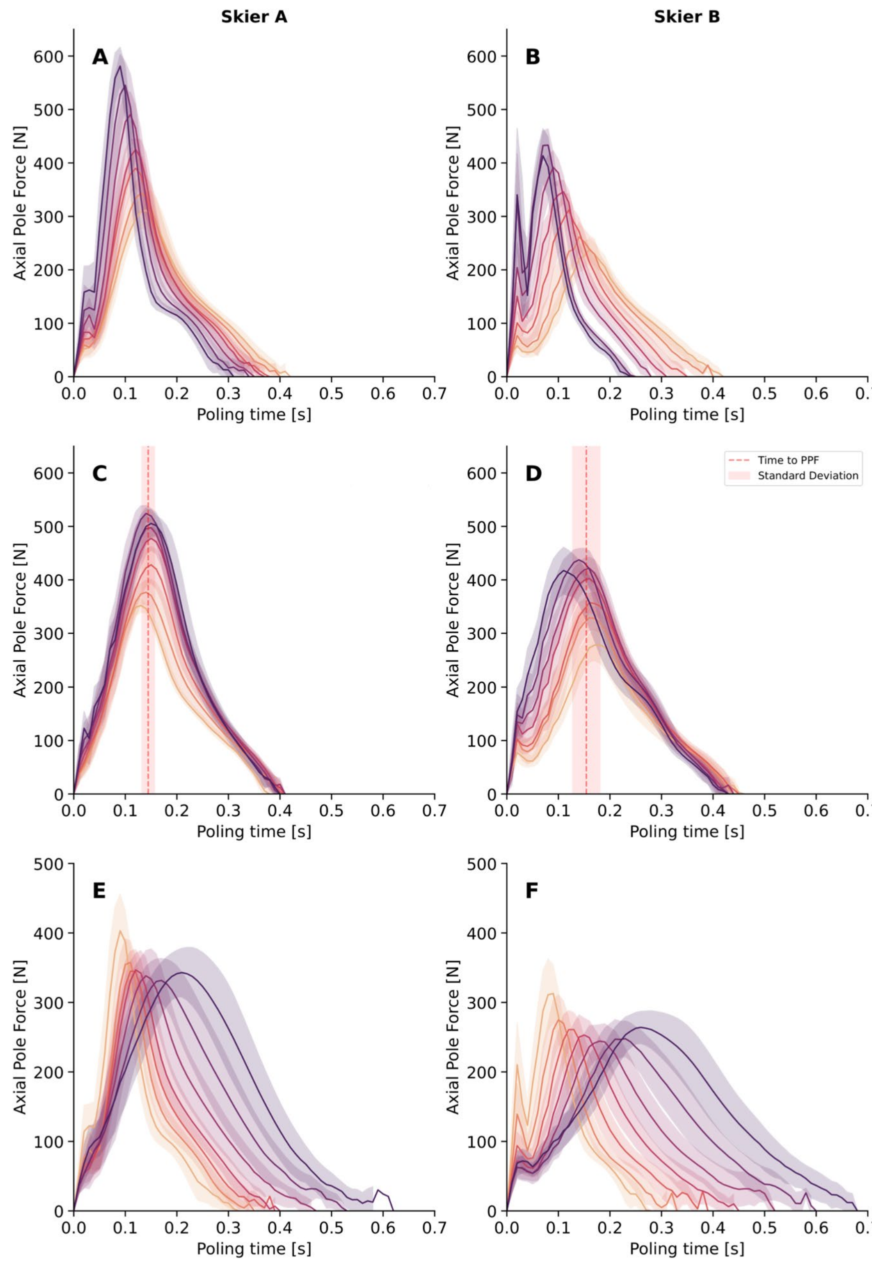

Fig. 3 Axial pole force as a function of poling time during the maximum speed (panels **A** and **B**), the maximum incline (panels **C** and **D**), and the constant-power-output (CPO) tests (panels **E** and **F**) for two participants (Skiers **A** and **B**) with similar performances ($v_{max} = 26.8$ km/h vs. 26.2 km/h respectively; $\alpha_{max} = 10°$ for both). Each panel presents seven mean pole force curves, which represent one-seventh of the total number of pole thrusts. The curves' hue darkens as the test time proceeds, indicating higher speed (for **A** and **B**), higher incline (for **C** and **D**), and steeper incline and lower speed (for **E** and **F**). Shaded areas represent $\pm$ SD. For the maximum incline tests, the mean time to peak pole force (PPF) $\pm$ SD (red dashed line and red shaded area) is also presented (panels **C** and **D**)

The simultaneous manipulation of speed and incline significantly affected most of the examined kinetic variables, revealing consistent trends across the ten test stages (Table 2). Notably, CR did not show a statistically significant change throughout the test. Instead, participants primarily adapted to the increasing incline by prolonging the poling time and increasing the axial pole force, which together led to a substantially increased poling impulse and PFR. Notably, the relative distribution of poling impulse, measured as the area under the axial pole force-time curve until and after the peak poling, relative to the total pole force impulse, remained constant across stages ($P = 0.64$). However, a substantial variation in the force-production demand arose across different speed-incline combinations. Specifically, the fraction of axial pole force directly devoted to propulsion decreased at higher speeds.

Accordingly, the CPO test results indicate that exercise demands in cross-country skiing cannot be accurately characterized by power output alone; speed, incline, or alternatively, the PFR should also be considered. This aligns with recent findings suggesting that when implementing the critical power concept to cross-country skiing, metabolic power should be considered [21]. Furthermore, it supports findings from gross efficiency research [22, 23], indicating that at a fixed submaximal power output, gross efficiency (i.e., the ratio of mechanical power output and metabolic power)

Table 2 Cycle characteristics and poling kinetics during the 10-min constant-power-output (CPO) test at inclines ranging between 1° and 7°

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	F	P	η_p^2
Treadmill incline [°]	1.0	1.2	1.5	1.9	2.4	2.9	3.7	4.5	5.6	7.0	–	–	–
Treadmill speed [km/h]	23.6 ± 1.8	21.1 ± 1.3	18.6 ± 1.2	16.3 ± 1.0	14.1 ± 0.9	12.0 ± 0.8	10.2 ± 0.6	8.6 ± 0.5	7.2 ± 0.4	6.2 ± 0.4	–	–	–
External power output [W]	187 ± 20	183 ± 20	183 ± 20	185 ± 20	188 ± 20	184 ± 20	188 ± 21	184 ± 20	185 ± 20	186 ± 20	$F_{3.2,44.5} = 101.7$	< 0.001	0.88
Poling impulse [Ns]	72 ± 15	77 ± 13	82 ± 15	91 ± 16	102 ± 18	114 ± 21	135 ± 23	150 ± 25	179 ± 28	208 ± 36	$F_{1.4,21.4} = 264.5$	< 0.001	0.95
Poling time [ms]	229 ± 17	246 ± 28	263 ± 32	287 ± 35	314 ± 39	342 ± 40	384 ± 43	422 ± 50	462 ± 56	517 ± 69	$F_{1.7,23.4} = 289.4$	< 0.001	0.95
Cycle time [ms]	1105 ± 159	1156 ± 91	1186 ± 93	1163 ± 91	1152 ± 90	1144 ± 88	1147 ± 87	1123 ± 92	1112 ± 86	1118 ± 102	$F_{1.9,26.4} = 2.6$	0.10	0.16
Swing time [ms]	876 ± 144	910 ± 86	922 ± 83	877 ± 81	838 ± 83	803 ± 80	763 ± 82	702 ± 75	649 ± 74	601 ± 72	$F_{1.7,24.1} = 125.8$	< 0.001	0.90
Relative poling time	0.21 ± 0.02	0.21 ± 0.02	0.22 ± 0.02	0.25 ± 0.03	0.27 ± 0.03	0.30 ± 0.03	0.34 ± 0.04	0.38 ± 0.04	0.42 ± 0.04	0.46 ± 0.04	$F_{1.9,27.7} = 866.8$	< 0.001	0.98
CR [cycles/min]	55.3 ± 8.3	52.5 ± 4.4	51.1 ± 4.3	52.1 ± 4.3	52.6 ± 4.4	52.9 ± 4.4	52.8 ± 4.2	53.9 ± 4.5	54.4 ± 4.5	54.1 ± 5.2	$F_{1.8,24.5} = 2.7$	0.10	0.16
CL [m]	7.3 ± 1.5	6.8 ± 0.7	6.1 ± 0.6	5.3 ± 0.5	4.5 ± 0.5	3.8 ± 0.4	3.2 ± 0.3	2.7 ± 0.3	2.2 ± 0.2	1.9 ± 0.2	$F_{1.3,18.9} = 490.4$	< 0.001	0.97
Axial pole force [N]	66 ± 6	68 ± 11	71 ± 12	79 ± 14	91 ± 16	102 ± 17	120 ± 19	136 ± 21	163 ± 24	187 ± 28	$F_{1.3,17.7} = 430.0$	< 0.001	0.97
Propulsive pole force [N]	27 ± 3	30 ± 3	34 ± 3	39 ± 4	46 ± 4	53 ± 5	64 ± 6	74 ± 7	89 ± 8	109 ± 10	$F_{1.0,14.0} = 1811.7$	< 0.001	0.99
Perpendicular pole force [N]	60 ± 6	61 ± 13	62 ± 14	69 ± 16	78 ± 18	87 ± 20	101 ± 22	114 ± 25	137 ± 28	151 ± 33	$F_{1.3,18.2} = 189.2$	< 0.001	0.93
PFR (F_{prop}/F_{axial})	0.42 ± 0.05	0.44 ± 0.09	0.48 ± 0.09	0.50 ± 0.10	0.51 ± 0.09	0.52 ± 0.09	0.53 ± 0.09	0.55 ± 0.09	0.55 ± 0.09	0.59 ± 0.08	$F_{2.1,30.0} = 63.0$	< 0.001	0.82
Impact pole force [N]	205 ± 20	177 ± 44	149 ± 45	137 ± 42	125 ± 41	106 ± 39	108 ± 42	104 ± 45	116 ± 49	119 ± 45	$F_{1.1,2.2} = 6.1$	0.12	0.75
Time to impact pole force [ms]	24 ± 2	25 ± 2	25 ± 2	27 ± 4	25 ± 4	31 ± 7	27 ± 6	31 ± 7	31 ± 3	33 ± 5	$F_{1.3,2.6} = 4.8$	0.13	0.71
Relative time to impact pole force	0.11 ± 0.01	0.10 ± 0.01	0.10 ± 0.01	0.10 ± 0.02	0.08 ± 0.02	0.09 ± 0.02	0.06 ± 0.03	0.06 ± 0.03	0.07 ± 0.01	0.06 ± 0.01	$F_{1.7,3.4} = 7.2$	0.06	0.78
Peak pole force [N]	281 ± 50	292 ± 43	301 ± 56	300 ± 62	306 ± 65	317 ± 64	334 ± 71	332 ± 76	343 ± 85	327 ± 70	$F_{1.8,20.3} = 0.7$	0.50	0.06
Time to peak pole force [ms]	82 ± 8	98 ± 13	110 ± 18	118 ± 19	133 ± 24	145 ± 35	160 ± 40	139 ± 59	192 ± 60	219 ± 65	$F_{2.3,25.8} = 27.7$	< 0.001	0.72
Relative time to peak pole force	0.37 ± 0.04	0.40 ± 0.04	0.42 ± 0.05	0.41 ± 0.05	0.42 ± 0.05	0.42 ± 0.07	0.41 ± 0.08	0.38 ± 0.09	0.41 ± 0.10	0.42 ± 0.10	$F_{1.9,19.0} = 1.1$	0.36	0.10

Table 2 Cycle characteristics and poling kinetics during the 10-min constant-power-output (CPO) test at inclines ranging between 1° and 7°

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	F	P	η_p^2
$\mathrm{RFD_{impact}}$ [kN/s]	8.5 ± 0.3	7.2 ± 2.0	6.0 ± 1.8	5.2 ± 1.6	5.0 ± 1.2	3.4 ± 1.4	4.0 ± 1.3	3.3 ± 1.0	3.6 ± 1.3	3.8 ± 1.7	$F_{1.3,2.7} = 11.8$	0.049	0.86
$\mathrm{RFD_{peak}}$ [kN/s]	6.5 ± 2.2	5.0 ± 1.7	4.2 ± 1.5	3.7 ± 1.4	3.0 ± 1.0	3.0 ± 1.2	2.8 ± 1.1	2.8 ± 1.4	2.7 ± 1.5	2.2 ± 1.5	$F_{1.6,14.0} = 22.9$	< 0.001	0.77
Impulse until peak pole force [Ns]	14.3 ± 3.1	16.9 ± 2.6	18.4 ± 3.7	19.5 ± 4.0	21.9 ± 4.9	24.6 ± 7.3	28.1 ± 8.1	30.2 ± 9.0	36.2 ± 11.1	45.8 ± 14.3	$F_{2.3,25.7} = 36.5$	< 0.001	0.77
Impulse after peak pole force [Ns]	23.4 ± 4.5	23.8 ± 4.2	27.5 ± 5.7	30.5 ± 6.4	34.3 ± 7.2	37.2 ± 8.2	45.1 ± 9.4	50.8 ± 11.2	58.4 ± 15.8	61.0 ± 14.3	$F_{2.2,24.1} = 68.7$	< 0.001	0.86
Relative impulse until peak pole force	0.38 ± 0.03	0.42 ± 0.02	0.40 ± 0.03	0.39 ± 0.03	0.39 ± 0.04	0.40 ± 0.07	0.38 ± 0.07	0.37 ± 0.08	0.38 ± 0.10	0.43 ± 0.09	$F_{2.8,31.1} = 0.6$	0.64	0.05
Relative impulse after peak pole force	0.62 ± 0.03	0.58 ± 0.02	0.60 ± 0.03	0.61 ± 0.03	0.61 ± 0.04	0.60 ± 0.07	0.62 ± 0.07	0.63 ± 0.08	0.62 ± 0.10	0.57 ± 0.09	$F_{2.8,31.1} = 0.6$	0.64	0.05

CR, cycle rate; CL, cycle length; PFR, pole force ratio; F_{prop}, propulsive pole force; F_{axial}, axial pole force; $\mathrm{RFD_{impact}}$, rate of force development of the impact pole force; $\mathrm{RFD_{peak}}$, rate of force development of the peak pole force

should increase with increasing incline. In this context, the observed declining trend in the PFR, together with previous findings on gross efficiency, suggest that the PFR may be linked to gross efficiency, indicating that alterations in the conversion of metabolic to mechanical power during double poling could be potentially explained by variation in poling mechanics.

Training load and training intensity distribution are topics of increasing attention in cross-country skiing and biathlon research [24–29]. As some studies have hypothesized [21, 30], the availability of accurate mechanical power output and work assessment would provide a significant improvement to the quantification of effort and external training load in these sports, and facilitate advanced performance analysis, as demonstrated in cycling [31, 32]. However, from a biomechanical standpoint and given the physiological evidence [22, 23], it appears that mechanical work could not provide a valid estimate of external training load, unless it is scaled for changes in gross efficiency, induced by external factors such as speed and incline.

4.2 Double-poling strategies

Studies have suggested two main double-poling strategies - the "wide elbow" and the "narrow elbow" strategies [8, 11]; furthermore, modern and old-fashioned double-poling techniques have also been distinguished [33]. These studies generally propose that the fastest cross-country skiers adopt double-poling strategies characterized by greater peak pole forces, higher poling impulse, and shorter relative poling time. Notably, it is not the impact pole force but rather the peak pole force that mainly contributes to propulsion. Some skiers can exhibit a high impact pole force but lose momentum in the next phase of the poling cycle, resulting in a considerable decline in pole force [34].

An example comparison of the axial pole force curves for two skiers, referred as Skier A and Skier B (Fig. 3), revealed remarkably different double-poling strategies despite their level of performance (i.e., difference in v_{max}: 0.6 km/h, $\alpha_{max} = 10°$ for both). Skier A applied consistently lower impact pole force across all tests than Skier B (and in some cases, no identifiable impact pole force at low speeds), yet demonstrated higher peak pole forces. This observation raises questions about the role and significance of the impact pole force in effective propulsion.

4.3 Cycle rate, poling impulse, and cycle length

For analyses of the simultaneous changes in poling impulse, CR and CL, it was observed that skiers with v_{max} slightly below the mean showed a greater decline in poling impulse throughout the maximum speed test than those with

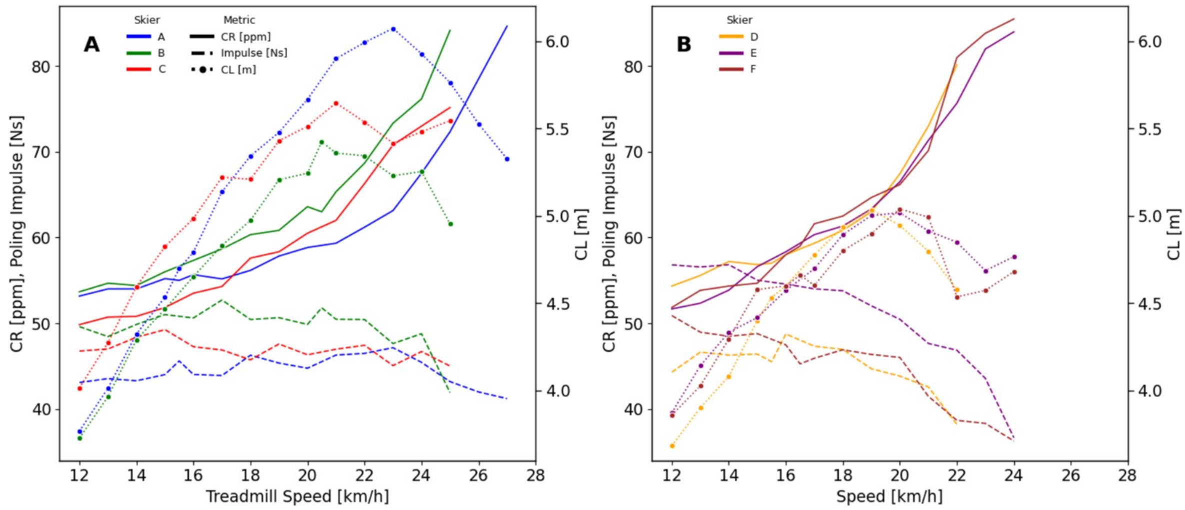

Fig. 4 Interactions between treadmill speed, cycle rate (CR), poling impulse and cycle length (CL) during maximum speed tests for three participants with maximum speeds above (panel **A**) and below the mean maximum speed (panel **B**). Data points represent mean values for each six-second stage

above-mean performances (see Fig. 4 for examples). CL typically peaked before the final stages of the test, coinciding with a disproportionately large increase in CR relative to the treadmill speed. Notably, the CR corresponding to $\mathrm{CL}_{\mathrm{peak}}$, here referred to as the "threshold CR", was around 60–65 polings per minute, and showed a relatively low inter-individual variation. Contrarily, there was no relationship found between the time interval from attaining $\mathrm{CL}_{\mathrm{peak}}$ to v_{max} (i.e., failure) and performance. This was likely due to substantial individual variation in the herein-called "CR reserve", which can be utilized by the participant after attaining $\mathrm{CL}_{\mathrm{peak}}$ to compensate for the decline in poling impulse.

Although Lindinger et al. [35] noted that cross-country skiers can increase speed through both CR and CL, considering the definition of CL as the ratio of speed to CR together with the findings of the present study, it appears that performance is better characterized by the skier's ability to maintain propulsive poling impulse at high speeds. Thus, a long CL is rather a consequence of effective force application than an individual performance determinant. This underscores the importance of strength training that is specific to cross-country skiing [36–38], as well as the need to develop technical and coordination skills, such as timing and balance, for improving v_{max}.

As CL represents speed expressed relative to CR, enhancing $\mathrm{CL}_{\mathrm{peak}}$ may be an effective strategy to improve v_{max}. Practically, a rightward shift of the CL curve (i.e., increased $\mathrm{CL}_{\mathrm{peak}}$ while maintaining the "CR reserve") would translate into a higher v_{max} (Fig. 4). Targeted training sessions performed under controlled conditions, near or slightly above the speed (and CR) corresponding to the $\mathrm{CL}_{\mathrm{peak}}$, could emphasize propulsive impulse development (i.e., $\text{poling impulse} \cdot \text{PFR}$) rather than CR increase, which may facilitate technique development and result in improved mechanical efficiency at high speeds. As it follows from its definition, propulsive impulse might be primarily developed through either increasing the applied pole force or PFR (i.e., decreasing the PFR decline from submaximal speeds to v_{max}); however, there was no relationship found between v_{max} and the degree of PFR decline.

Poling time is primarily determined by skiing speed, anthropometrics and pole length (which is regulated by rules in classical cross-country skiing), with its lower bound constrained by neuromuscular control and the contractile speed of the recruited muscles, which vary with individual fibre type composition [39, 40]. Notably, since a very strong relationship was found between poling time and the PFR, limitations posed to poling time are likely determinants of the PFR as well. In the current study, faster participants reached an approximately 10% higher v_{max} relative to their slower counterparts. Nevertheless, no association was found between the minimum poling time and v_{max} ($r = 0.16$, $P = 0.57$), highlighting the importance of generating great pole forces in the maximum speed test. Minimum poling time in the maximum speed test was consistent with previous findings at a $1°$ incline [34], showing 11% variation across participants and suggesting a physical limit around $180 - 220$ ms. For context, this duration is about 25–60% longer than typical ground contact times in the long jump [41].

4.4 Limitations

This study included only male cross-country skiers, which limits the generalizability of some of the presented findings.

For example, research has shown that female cross-country skiers typically exhibit higher cycle rates than males [42, 43], which may suggest sex-related differences in the interaction among cycle rate, poling impulse, and cycle length, as well as potential differences in the "threshold CR" and "CR reserve".

Double-poling biomechanics were investigated at the cycle level without incorporating kinematic measurements. Consequently, the methodology did not allow for the detailed analysis of propulsion dynamics within individual poling cycles, which should be addressed in future research.

Pole force data were extracted from the ski pole handles at a sampling rate of 100 Hz, which limited the temporal resolution of the assessed variables. Consequently, results for variables that are sensitive to sampling frequency, such as the timing of the impact pole force and the rate of force development, should be interpreted with caution.

In the CPO test, minor variations in external power output occurred between stages, resulting in statistically significant differences across stages (Table 2). These variations stemmed from the inherent limitations in the accuracy of treadmill speed and incline settings (± 0.1 km/h and $\pm 0.1°$, respectively). However, considering the typical measurement error of 1.6 W relative to the mean power output ($\sim 185 \pm 20$ W), the protocol and corresponding test results were considered to reflect a constant-power-output condition adequately [44].

Although the rolling friction coefficient (μ_r) was measured following a warm-up of the wheel bearings, minor fluctuations in μ_r may have occurred due to its temperature and normal-force sensitivity [45]. Based on the participants' mean body mass and the mean prescribed velocities in the CPO test, ± 0.001 deviation from the measured value (i.e., $\mu_r = 0.018$) would have resulted in an absolute difference in frictional power ranging from approximately 1.3 to 5 W, with a linear increase at higher speeds.

4.5 Future directions

Currently, little is known about the potential of the novel maximum incline test for performance assessment. The high demands on propulsive pole force and impulse generation observed in this test suggest that it may serve as a practical means of evaluating maximum power output and acceleration capacity in cross-country skiers. Nevertheless, further research is required to validate its relevance to on-snow race performance. Additionally, the present findings support future research into the PFR and potential relationships with physiological parameters, such as gross efficiency and skiing economy. Furthermore, these findings suggest that technological development should focus on assessing skiers' power output directly at the poles and ski bindings. In addition, there is a need to develop methods for estimating metabolic work from mechanical work while accounting for external factors, as these factors are crucial for obtaining valid estimates of external training load.

5 Conclusions

This study provides insights into the biomechanics of cross-country skiing, being the first to examine double poling under constant propulsive force, speed, and power output conditions, with a particular focus on cycle characteristics and poling kinetics. The results indicate that the maximum speed and maximum incline tests pose considerably different biomechanical requirements for cross-country skiers and demonstrate that faster skiers are not necessarily superior on steep gradients. The main finding of the present work is that, from a biomechanical perspective, external power output alone is insufficient for accurately quantifying exertion in cross-country skiing unless speed or incline are also considered. Consequently, neither can external work provide a valid measure of external training load without addressing these factors. Additionally, this study demonstrates the potential of biomechanical analyses of axial pole force data and cycle characteristics for skiing technique refinement and the development of targeted training strategies to enhance double-poling performance. In particular, the findings suggest that training at or near the peak cycle length may represent an effective approach for enhancing maximum skiing speed.

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Data availability Data is provided as mean $\pm$ standard deviation in the manuscript to describe trends and changes on a mean level. Furthermore, data representing results from certain participants are also provided in the form of anonymised figures. Access to additional data repositories can be requested from the corresponding author upon a reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

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