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ORIGINAL ARTICLE

Do poles really "save the legs" during uphill pole walking at different intensities?

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Abstract

Purpose In sky- and trail-running competitions, many athletes use poles. The aims of this study were to investigate whether the use of poles affects the force exerted on the ground at the feet (Ffoot), cardiorespiratory variables and maximal performance during uphill walking.

Methods Fifteen male trail runners completed four testing sessions on different days. On the first two days, they performed two incremental uphill treadmill walking tests to exhaustion with (PW_{incr}) and without poles (W_{incr}). On the following days, they performed submaximal and maximal tests with (PW_{80} and PW_{max}) and without (W_{80} and W_{max}) poles on an outdoor trail course. We measured cardiorespiratory parameters, the rating of perceived exertion, the axial poling force and Ffoot.

Results When walking on the treadmill, we found that poles reduced maximum Ffoot ($-2.8 \pm 6.4\%$, $p = 0.03$) and average Ffoot ($-2.4 \pm 3.3\%$, $p = 0.0089$). However, when outdoors, we found pole effect only for average Ffoot ($p = 0.0051$), which was lower when walking with poles ($-2.6 \pm 3.9\%$, $p = 0.0306$ during submaximal trial and $-5.21 \pm 5.51\%$, $p = 0.0096$ during maximal trial). We found no effects of poles on cardiorespiratory parameters across all tested conditions. Performance was faster in PW_{max} than in W_{max} ($+2.5 \pm 3.4\%$, $p = 0.025$).

Conclusion The use of poles reduces the foot force both on the treadmill and outdoors at submaximal and maximal intensities. It is, therefore, reasonable to conclude that the use of poles "saves the legs" during uphill without affecting the metabolic cost.

Keywords Trail running · Uphill · Vertical km · Ground reaction forces · Poling forces

Abbreviations

ANOVA	Analysis of variance
BLC	Blood lactate concentration
fDF	Foot duty factor
Ffoot	Foot force
Fpole	Poling force
ΔFfoot	Difference in Ffoot between PW_{incr} and W_{incr}
GET	Gas exchange threshold
HR	Heart rate
ITRA	International trail running association
NW	Nordic walking
pDF	Pole duty factor
PW	Pole walking
PW_{80}	Pole walking at 80% of RCP
PW_{incr}	Pole walking incremental treadmill test
RCP	Respiratory compensation point
RPE	Rating of perceived exertion
Tcfoot	Foot contact phase
Tcpole	Poling phase time
Tfoot	Foot cycle time
Tpole	Pole cycle time
$\dot{V}_E$	Volumetric flow rate of expired air
$\dot{V}CO_2$	Rate of carbon dioxide production
$\dot{V}O_2$	Rate of oxygen uptake rate
v_{vert}	Vertical velocity
W	Walking
W_{80}	Walking at 80% of RCP
W_{incr}	Walking incremental treadmill test

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Introduction

In sky- and trail-running competitions, many athletes use poles (see Scheer et al. (2020) for further information about the differences between these disciplines). The conventional wisdom is that they improve performance, but thus far, only one study (Giovanelli et al. 2022b) has demonstrated that the use of poles allows for faster performance during maximal uphill efforts, whereas submaximal performance at about 70% of maximal oxygen uptake ($\dot{V}O_2max$) is not affected by the use of poles (Giovanelli et al. 2022b). Thus, it is not clear why maximal performance is improved. The authors speculated that on steep terrain, efficiency was higher with poles, in part because some of the work was redistributed to the upper limbs (Pellegrini et al. 2015).

It is reasonable to assume that during locomotion, the more force applied via the poles, the less pressure and force are applied at the feet. Some authors find that using poles decreases plantar pressure during level walking (Encarnacion-Martinez et al. 2017; Perez-Soriano et al. 2011). This is likely due to the use of poles as "additional points of support". However, as recently reviewed (Hawke and Jensen 2020), research has shown conflicting results regarding vertical ground reaction forces, or foot forces (Ffoot) with the use of poles. Indeed, some reported a decrease in Ffoot when poles were used (Willson et al. 2001), while others reported no changes (Jensen et al. 2011) or higher Ffoot peaks (Hagen et al. 2011; Encarnacion-Martinez et al. 2015). It is important to note that in the Encarnacion-Martinez et al. study, walking speed was faster when poles were used. Dziuba et al. (2015) reported no differences in kinematic and kinetic parameters during pole walking (PW), with the exception of a slightly higher Ffoot in the first phase (load acceptance) and a reduction in the second phase (corresponding to the push-off phase). Notably, these studies were conducted on level surfaces and do not provide information on the use of poles during steep uphill walking, which characterizes sky- and trail-running events (Giovanelli et al. 2016). To date, only a few investigations have been conducted on slope walking and found that using poles decreases Ffoot during level and downhill (-6°) when running at 3.2 m/s (Daviaux et al. 2013). Conversely, during uphill (9°) walking, there were no differences in Ffoot (Daviaux et al. 2013), and the authors suggested a redistribution of the mechanical work from the lower to the upper limbs. Significant reduction in ground reaction forces, knee joint moment, tibiofemoral compressive and shear forces have been found when using trekking poles during downhill walking (− 25°) (Schwameder et al. 1999).

Data about poling force published for cross-country skiing may be of interest, especially those describing the diagonal stride technique that involves a similar coordination pattern between arms and legs as in trail running. Two cross-country skiing studies reported that increasing the uphill gradient increased the poling force, while increasing the speed had no effect on poling force (Pellegrini et al. 2011, 2013). In addition, in cross-country skiing, especially in the diagonal stride technique on flat terrain, the use of poles has been shown to reduce the vertical ground reaction forces measured under roller skis (Kehler et al. 2014). Furthermore, the upper limb contribution to the total power exerted (upper + lower limbs) decreased from approximately 30% up a 2 degree incline to approximately 24% at 8° (Pellegrini et al. 2011).

The aims of this study of uphill pole walking were to measure i) the forces exerted via the poles and ii) the changes in Ffoot facilitated by using poles at different intensities during an incremental uphill walking test and during two, submaximal and maximal, outdoor tests on a mountain path. Since there were no studies investigating poling forces during steep uphill walking, we based our hypothesis on a similar movement (diagonal stride during cross-country skiing) (Pellegrini et al. 2011, 2013). Thus, we hypothesized that poling forces would increase on steeper uphill gradients. We also hypothesized that Ffoot would be lower when athletes used poles in uphill walking compared to without poles. Specifically, and differently from level pole walking, we expected a significant decrease in Ffoot because usually athletes position the pole more vertically during uphill walking to exert a useful push upwards, especially on steep incline.

Methods

Participants

We enrolled 15 male trail runners (age: 36.8 ± 6.8 years; body mass: 69.9 ± 4.7 kg; height: 1.753 ± 0.049 m; International Trail Running Association (ITRA) Performance Index: 667.8 ± 121.4) who were experts in using poles during trail running (6.4 ± 4.5 years of experience with poles). Based on ITRA Performance Index the athletes we enrolled can be included in the category "Advanced", even if some of them are "Top Elite". "The ITRA Performance Index is a tool for ranking athletes based on their performance level. […] Male elite athletes score over 825 points, […]." (www.itra.run). They provided informed consent according to the guidelines of the Declaration of Helsinki and approved by the Institutional Review Board of the University of Udine (IRB 57/2022).

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Experimental design

Participants completed four testing sessions on four different days, with at least 48 h of rest or light exercise between them. On the first two days, they performed two uphill incremental tests to exhaustion on a treadmill with and without poles in random order. On the third and fourth days, they performed submaximal and maximal tests with and without poles on an outdoor trail course with 150 m of elevation gain. After completing every trial, participants were required to return to the starting point by walking downhill and then they rested five minutes before starting for the subsequent trial.

The intensities of the submaximal outdoor tests with (PW_{80}) and without poles (W_{80}) were set at 80% of the vertical velocity corresponding to the respiratory compensation point (RCP) determined during the incremental treadmill test (Beaver et al. 1986). PW_{80} and W_{80} were performed in random order on the third day and were reversed on the fourth day. After the two submaximal trials, they completed one more uphill trial at their maximal effort, one day with poles (PW_{max}) and one day without (W_{max}), in random order.

During the tests, we recorded cardiorespiratory parameters, foot forces (Ffoot, in N) and rating of perceived exertion (RPE). During the test performed with the poles, pole length (on average 65.6 ± 1.8% of participant's height) and pole walking technique were self-selected and we recorded axial poling forces (Fpole, in N). To note that the subjects used a diagonal stride technique on treadmill, whereas outdoors they adopted a more variable pattern that included different time coordination between poles and legs depending on the trail surface.

Incremental treadmill test

We determined the maximum-, RCP- and gas exchange threshold (GET)-related parameters ($\dot{V}O_2$, heart rate (HR), vertical velocity (v_{vert})) during two incremental tests on a customized treadmill. We modified a treadmill (Sapilo, Cittadella, Italy) to accommodate a wide belt (0.65 m × 1.60 m) so that the pole tips could be placed on the moving belt. Further, the treadmill was attached to an external metal frame that could be inclined up to 45°. This same protocol was performed one day with poles (PW_{incr}) and one day without poles (W_{incr}), in a randomized order on the same treadmill. Every subject started at 1.1 m/s and an incline of 6.5°. The speed remained unchanged for the duration of the test while an operator increased the incline by 1.43 ± 0.11° every minute until the volitional exhaustion of the participant. This protocol increased the vertical velocity by 0.026 ± 0.001 m/s every minute. We determined the RCP and GET using the V-slope method (Beaver et al. 1986).

Outdoor tests

Participants performed two submaximal trials of 150 m of elevation gain on a mountain trail (350 m length, 26.5° maximum incline, 23.2° average incline) with the surface characteristics described elsewhere (Giovanelli et al. 2022a, b). One trial was performed with poles (PW_{80}) and one without poles (W_{80}), in randomized order. In a previous study, we determined that, during outdoor walking on this trail, the same metabolic demand was obtained at a speed 7.9% slower than the speed during treadmill walking (Giovanelli et al. 2022b). Thus, we calculated 80% of the vertical velocity corresponding to RCP detected during laboratory incremental treadmill tests and then we subtracted the 7.9% to obtain the target vertical velocity to maintain outdoors. To maintain the target v_{vert}, we marked the course every 25 m of elevation, and an experienced investigator paced all the athletes. We then asked participants to complete another uphill trial at maximum effort. In random order, they performed a maximal trial one day with poles and one day without.

During all tests, we measured $\dot{V}O_2$, carbon dioxide production ($\dot{V}CO_2$), HR, and Ffoot. Furthermore, during PW_{80} and PW_{max}, we measured the pole forces. Before and 1 min after the end of the test, we measured the blood lactate concentration from collecting mixed venous blood at the earlobe (BLC; Lactate Scout 4, EKF Diagnostic, UK).

Metabolic measurements

During all tests, we measured $\dot{V}O_2$ and $\dot{V}CO_2$ using a metabolic unit (K5, Cosmed, Rome, Italy). All the measurements were performed with the function "mixed chamber". Before every test we calibrated the gas analyzers and flowmeter as suggested by the manufacturer. Additionally, we measured HR using a HR chest strap (HRM-Dual™, Garmin, Olathe, Kansas, USA) associated with the metabolic unit.

Force measurements

During all tests we measured the force applied at the foot by using instrumented insoles (Loadsol®, Novel, Munich, Germany). During the PW_{incr}, PW_{80} and PW_{max} we measured the axial forces applied on poles by a 15 g single-axial force transducer (Deltatech, Sogliano al Rubicone, Italy) inserted beneath each handgrip (Pellegrini et al. 2018) of pair of length-adjustable poles (Inverso-Alu, Gabel, Rosà, Italy). We acquired both foot and pole forces at 100 Hz, and data were subsequently analysed for the middle portion of each gradient stage during the incremental treadmill test and for the whole duration of the outdoor test. From the force−time curve for each analysed cycle we extracted the following parameters: foot and pole cycle time (Tfoot and Tpole, in s), foot contact time (Tcfoot, in s) and poling phase

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time (Tcpole, in s) and duty factor (fDF = Tcfoot/Tfoot and pDF = Tpole/Tcpole for foot and pole, respectively), and foot and poling force (Ffoot and Fpole, in N) averaged over the entire poling cycle.

Rating of perceived exertion

During PW_{incr} and W_{incr}, we asked the subjects to rate their overall perceived exertion every minute (i.e., during the last 10 s of each stage) using the Borg 6–20 Scale (Borg 1970). During PW_{80}, W_{80}, PW_{max} and $W_{max,}$ we asked the subjects to evaluate their RPE at the end of each trial.

Statistical analysis. For all the analysis, we used GraphPad Prism version 9.3.1 (GraphPad Software, San Diego, California, USA) and the significance level was set at $p < 0.05$. For both foot and pole parameters, we analysed whether there were differences between the left and right sides using a t-test. Since we did not find differences in any of the analysed parameters, we averaged the values for the left and right sides.

First, we analysed the incremental treadmill test. After checking that parameters were normally distributed, we applied a paired two-tailed *t* test comparing PW_{incr} and W_{incr} for maximal cardiorespiratory values and vertical velocity.

We analysed cardiorespiratory parameters and foot force-related parameters (i.e., Tfoot, fDF, maximum and average Ffoot) with a two-way ANOVA or mixed-effects (when missing values were present) with the Geisser–Greenhouse correction. We considered two factors (*Condition*: PW and W; *Gradient*: from the first to the eleventh stage). In this analysis we considered only the first eleven stages of the incremental treadmill test because they were completed by all subjects. Then, we applied the Holm-Šidak post hoc test to compare each parameter with others at the same incline.

We tested the poling-related parameters (i.e., Tpole, Tcpole, average Fpole, pDF) with a repeated measures one-way ANOVA, with the Geisser-Greenhouse correction. Different *gradients* were represented by the first eleven stages of the incremental treadmill test.

In order to investigate whether the use of poles reduces Ffoot in comparison to walking without poles, we calculated for each subject at each stage of the incremental treadmill test the difference in Ffoot between PW_{incr} and W_{incr} (ΔFfoot). Afterwards, we calculated the correlation between the Fpole during PW_{incr} and ΔFfoot.

Then, we analysed the outdoor test. For poling force-, foot- and cardiorespiratory parameters we averaged the data for the entire duration of every trial. Then, parameters of the submaximal tests (PW_{80} and W_{80}) acquired during Day 1 and Day 2 were compared by using a paired two-tailed *t* test and if they were not statistically different, the two values were averaged for both PW_{80} and W_{80}. Furthermore, we analysed the data with a two-way ANOVA or mixed-effects (when missing values were present) with the Geisser–Greenhouse correction. We considered two factors (*Condition*: PW and W; *Intensity*: 80% and Max). Then, we applied the Holm-Šidak post hoc test to compare each parameter with others.

We compared the poling-related parameters with a paired two-tailed t test comparing PW_{80} and PW_{max}.

Results

Incremental treadmill test

Cardiorespiratory values. We found no differences ($p > 0.05$) in maximal cardiorespiratory parameters nor in the fastest vertical velocity reached between PW_{incr} and W_{incr}. However, v_{vert} (as a percentage of the maximum v_{vert} reached) and RPE at RCP, as well as the RPE at GET were lower during PW_{incr} in comparison to W_{incr} (Table 1). We found no effects of poles on the cardiorespiratory parameters ($p > 0.05$).

Foot-parameters. The mixed-model revealed *Condition* effects for foot cycle time ($p = 0.0045$, $F(1.000, 14.00) = 11.41$) and foot contact time ($p = 0.0035$, $F(1.000, 14.00) = 12.25$) both were lower in W_{incr} in comparison to PW_{incr}. Conversely, maximum Ffoot ($p = 0.030$, $F(1.000, 14.00) = 5.781$) and average Ffoot ($p = 0.0089$, $F(1.000, 14.00) = 9.213$) were lower in PW_{incr} in comparison to W_{incr} (Fig. 1). Numerically, maximum Ffoot was $-2.8 \pm 6.4\%$ lower during PW_{incr} in comparison to W_{incr}. Also, average Ffoot was $-2.4 \pm 3.3\%$ lower during PW_{incr} in comparison to W_{incr}.

There was a *Gradient* effect for all the aforementioned parameters. In fact, foot cycle time ($p = 0.0016$, $F(1.496, 20.95) = 10.37$) and foot contact time ($p = 0.0096$, $F(1.504, 21.05) = 6.64$) decreased throughout the test, whereas maximum Ffoot ($p < 0.0001$, $F(1.769, 24.77) = 24.50$), average Ffoot ($p = 0.0055$, $F(1.391, 19.47) = 8.20$) and foot duty cycle ($p = 0.0013$, $F(2.366, 33.13) = 7.47$) increased throughout the test (Fig. 1).

Poling-parameters. One-way ANOVA revealed that increasing the gradient on treadmill decreased Tpole ($p = 0.0159$, F $(2.347, 32.85) = 4.397$). Conversely, on steeper gradients, average Fpole ($p < 0.0001$, F $(3.960, 55.45) = 48.64$) and duty cycle ($p < 0.0001$, $F(4.856, 67.98) = 16.03$) increased (Fig. 2). Across gradients, Tcpole did not change ($p = 0.269$, F $(3.074, 43.04) = 1.354$). There was a correlation between Fpole and the change in Ffoot when poles were used ($r = 0.52$, $p < 0.0001$; Fig. 3).

Outdoor test

The four submaximal trials lasted (in min:sec): 08:00 ± 01:08 (W_{80} Day 1), 07:57 ± 01:11 (W_{80} Day 2), 08:01 ± 01:09 (PW_{80} Day 1), 07:58 ± 01:10 (PW_{80} Day 2) (time effect

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Table 1 Metabolic parameters of the participants measured during the incremental treadmill test ($n = 15$)

	PW_{incr} Mean ± SD	W_{incr} Mean ± SD	p
Maximal Values			
$\dot{V}O_2$max (ml/kg/min)	62.7 ± 8.9	61.5 ± 7.0	0.097
v_{vert} max (m/s)	0.497 ± 0.06	0.496 ± .052	0.723
HR max (bpm)	179.2 ± 11.3	180.8 ± 11.2	0.144
RPE max	20 ± 0.0	19.9 ± 0.3	0.336
Respiratory compensation point			
$\dot{V}O_2$ (ml/kg/min)	52.3 ± 7.0	50.8 ± 6.2	0.111
$\dot{V}O_2$ (%max)	83.7% ± 0.05%	84.3% ± 0.06%	0.153
HR (bpm)	166.9 ± 12.3	168.7 ± 12.4	0.306
HR (%max)	93.3% ± 2.4%	93.30% ± 2.5%	0.918
v_{vert} (m/s)	0.412 ± 0.061	0.424 ± 0.05	0.108
v_{vert} (%max)	82.5% ± 4.0%	85.5% ± 4.1%	0.006
RPE	15.8 ± 1.5	16.9 ± 1.6	0.006
Gas exchange threshold			
$\dot{V}O_2$ (ml/kg/min)	42.9 ± 6.0	43.6 ± 5.2	0.408
$\dot{V}O_2$ (%max)	68.9% ± 4.5%	72.3% ± 6.2%	0.003
HR (bpm)	149.9 ± 11.6	151.5 ± 11.8	0.347
HR (%max)	84.0% ± 4.3%	83.9% ± 5.1%	0.625
v_{vert} (m/s)	0.336 ± 0.051	0.346 ± 0.042	0.085
v_{vert} (%max)	67.5% ± 4.6%	69.8% ± 4.5%	0.054
RPE	12.5 ± 1.5	14.1 ± 0.8	0.002

Values are presented as mean ± SD

PW pole walking, *W* walking, $\dot{V}O_2$ oxygen uptake, v_{vert} vertical velocity, *HR* heart rate, *RPE* rating of perceived exertion

$p = 0.0247$, F (1.000, 12.00) = 6.591, condition effect, $p = 0.1862$, F (1.000, 12.00) = 1.966). These durations correspond to vertical velocities (in m/s) of: 0.319 ± 0.048 (W_{80} Day 1), 0.321 ± 0.050 (W_{80} Day 2), 0.318 ± 0.048 (PW_{80} Day 1), 0.320 ± 0.049 (PW_{80} Day 2) (time effect $p = 0.0252$, F (1.000, 12.00) = 6.531, condition effect, $p = 0.1463$, F (1.000, 12.00) = 2.412).

Condition vs. Intensity

Cardiorespiratory values. The two-way ANOVA revealed *Intensity* effects on $\dot{V}O_2$ ($p < 0.0001$; F(1.000, 12.00) = 73.26), $\dot{V}_E$ ($p < 0.0001$; F(1.000, 12.00) = 114.0), HR ($p < 0.0001$; F(1.000, 12.00) = 150.1), BLC ($p < 0.0001$; F(1.000, 12.00) = 173.8) and RPE ($p < 0.0001$; F(1.000, 12.00) = 893.2). All of these parameters were higher during PW_{max} and W_{max} compared to PW_{80} and W_{80}. In contrast, there were no *Condition* effects for these parameters (i.e., PW vs. W).

Foot-parameters. There were *Intensity* effects for foot cycle time ($p < 0.0001$; F(1.000, 12.00) = 90.38) and foot contact time ($p < 0.0001$; F(1.000, 12.00) = 79.83) that were lower during PW_{max} and W_{max} in comparison to PW_{80} and W_{80}. In contrast, maximal Ffoot was higher during the maximal trials compared to submaximal trials ($p = 0.0083$; F(1.000, 12.00) = 9.969) (Table 2).

We found a *Condition* effect only for average Ffoot ($p = 0.0051$; F(1.000, 12.00) = 11.65), which was lower during PW_{max} and PW_{80} in comparison to W_{max} and W_{80} (− 2.6 ± 3.9%, p = 0.0306 at submaximal trial and − 5.21 ± 5.51%, p = 0.0096 at maximal trial).

PW_{max} vs. PW_{80} poling-related parameters. Poling cycle time was shorter during PW_{max} compared to PW_{80} (− 14.6 ± 19.7%, $p = 0.025$). Average poling force was higher in PW_{max} compared to PW_{80} (+ 12.4 ± 18.1%, $p = 0.012$) (Table 3).

PW_{max} vs. W_{max}

Metabolic values and vertical velocity. No differences were detected in cardiorespiratory parameters but maximal vertical velocity was faster in PW_{max} than in W_{max} (+ 2.5 ± 3.4%, p = 0.025).

Foot-parameters. Post hoc test revealed that during PW_{max}, average Ffoot was lower than during W_{max}

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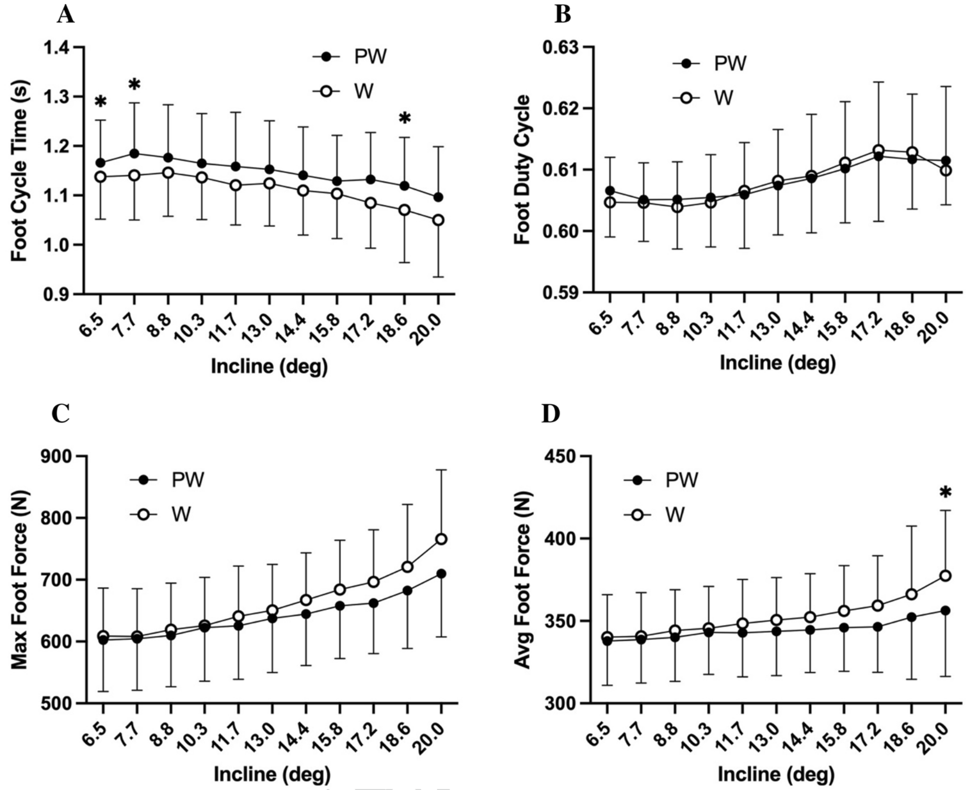

Fig. 1 Foot cycle time (in s, **A**), duty cycle (**B**), maximum Ffoot (in N, **C**), average Ffoot. (in N, **D**) as a function of the incline during the incremental treadmill test. PW: pole walking; W: walking. *$p < 0.05$, compared with walking

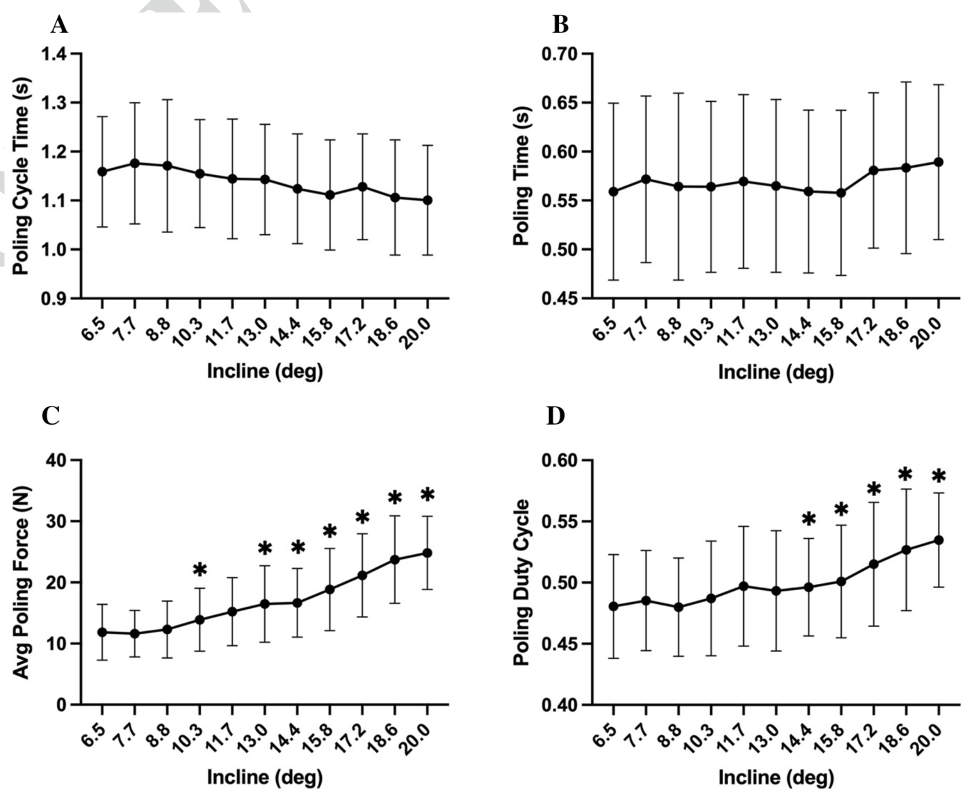

Fig. 2 Poling cycle time (in s, **A**), poling time (in s, **B**), average poling force (in N, **C**), poling duty cycle (**D**) as a function of the incline during the incremental treadmill test. PW: pole walking; W: walking. *$p < 0.05$ compared with the first stage (6.5 deg)

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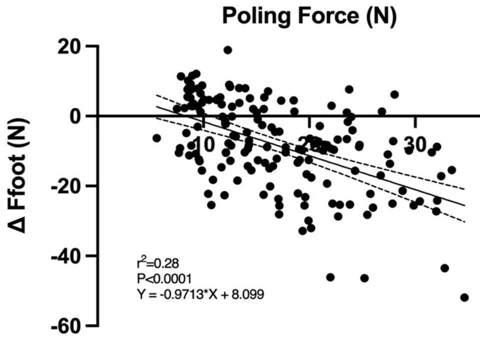

Fig. 3 Correlation between poling force (in N) and the difference between the foot force measured during the trial with (PW) and without poles (W) on treadmill (ΔFfoot). Dashed lines represent 95% confidence interval

(− 5.21 ± 5.51%, p = 0.022) whereas the other parameters were not different between the two conditions.

Discussion

The main findings of the present study were that the axial forces on poles increased on steeper inclines. When athletes used poles, the foot force decreased, both on treadmill and outdoors, during both submaximal and maximal tests. On the treadmill, the decrease in Ffoot correlated with the greater Fpole and the use of poles resulted in longer cycle time and, thus, longer stride length.

In our first hypothesis, we sustained that axial poling forces would increase on steeper uphill gradients, as for cross-country skiing. Although there is no gliding phase during uphill walking as in cross-country skiing, and speed, step length and pole length are lower, our hypothesis was confirmed. Indeed, during the incremental treadmill test, Fpole increased on steeper inclines. Compared to similar inclines, Fpole is greater for cross-country skiers (Pellegrini et al. 2011). At lower inclines (up to 8 deg), the forces applied on ski poles are similar to those exerted during level pole walking (Pellegrini et al. 2018). However, at the steeper gradients reported here, Fpole was more than double the force applied during level pole walking. In our study, the use of poles on the treadmill decreases both the average and maximum Ffoot, particularly on steeper inclines (Fig. 1C, D). In addition, we showed that during the treadmill test, participants who exerted more force on the poles exhibited a greater decrease in Ffoot. These data suggest that subjects who pushed harder with the poles needed to push less with their legs.

From a practical point of view, the results obtained outdoors are of greater importance. Indeed, average Ffoot during maximal effort was ~ 5% lower when subjects used poles (~ 20 N lower). Moreover, during the submaximal trials, the forces applied on the insoles were ~ 3% lower when subjects used poles. It is usually said that using poles when walking uphill "saves the legs". With this expression athletes mean that the effect of fatigue on lower limbs muscles

Table 3 poling-related parameters during pole walking at maximum intensity (PWmax) and 80% (PW80)

	PW_{80} Mean ± SD	PW_{max} Mean ± SD	*p*
Poling cycle time (s)	1.90 ± 0.32	1.61 ± 0.39	0.025
Poling time (s)	1.04 ± 0.18	0.90 ± 0.25	0.058
Poling duty factor (%)	54.6 ± 4.7	55.7 ± 4.5	0.126
Average poling force (N)	20.3 ± 4.7	23.2 ± 7.0	0.012

Table 2 Foot-related parameters, cardiorespiratory parameters, blood lactate concentration and rating of perceived exertion for pole walking (PW) and walking (W) during the outdoors trials at submaximal (80%) and maximum intensity

	80%		Max		I	C	I x C
	PW	W	PW	W			
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD			
Contact time (s)	0.73 ± 0.1	0.76 ± 0.1	0.55 ± 0.13	0.54 ± 0.12	< 0.001	0.556	0.203
Foot cycle time (s)	1.2 ± 0.1	1.2 ± 0.1	0.97 ± 0.1	0.97 ± 0.1	< 0.001	0.944	0.601
Foot duty factor (%)	60.3 ± 2.3	62.5 ± 6.7	56.3 ± 6.0	55.6 ± 6.1	0.002	0.406	0.137
Max foot force (N)	968 ± 104.8	996 ± 115	1039 ± 143.9	1093 ± 189	0.008	0.067	0.462
Average foot force (N)	382 ± 33.6	392 ± 36.2	371.0 ± 35.1	392 ± 33.1	0.100	0.005	0.065
Oxygen uptake (ml/min)	2876 ± 270	2902 ± 325	3707 ± 475	3600 ± 527	< 0.001	0.314	0.171
Carbodioxide production (ml/min)	2570 ± 214	2653 ± 306	3787 ± 543	3791 ± 540	< 0.001	0.256	0.435
Ventilation (L/min)	75.6 ± 9.1	77 ± 11.7	122 ± 21.1	122 ± 20.5	< 0.001	0.734	0.473
Heart rate (bpm)	141 ± 11.1	141 ± 12.3	161 ± 11.9	164 ± 12.7	< 0.001	0.137	0.090
Blood lactate concentration (mmol/L)	1.8 ± 0.5	2.2 ± 0.7	6.9 ± 1.7	7.7 ± 2.8	< 0.001	0.199	0.570
Rating of perceived exertion	12.1 ± 1.0	12.6 ± 1.3	18.7 ± 0.9	18.7 ± 1.0	< 0.001	0.244	0.244

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can be limited by the use of poles even though it has not been shown or quantified previously. Interestingly, previous research showed a reduction in foot forces when running with poles at 3.2 m/s on the flat and downhill, but no differences on a 9° uphill incline (Daviaux et al. 2013). The present results are of great interest to trail running coaches and athletes because we reported and quantified for the first time that the force applied to the poles effectively reduces the load on the foot and may have a protective effect that delays fatigue and protects against common trail running injuries, especially in the long term activity (Vernillo et al. 2016). With this finding, we also confirm our second hypothesis that Ffoot would be lower when athletes used poles in uphill walking compared to without poles.

Regarding cardiorespiratory parameters, no differences were found between using or not using poles at the same vertical velocity, both on treadmill and outdoor. This is in contrast to other studies that have reported that the use of poles increased energy expenditure because greater muscle mass was involved (Sugiyama et al. 2013; Pellegrini et al. 2015, 2018). However, it should be noted that greater energy expenditure was frequently found during level pole walking, but, as the incline was increased, the difference in energy expenditure between using poles or not using poles decreased (Pellegrini et al. 2015). When the gradient becomes steeper than in the present study (above 25°), it has been demonstrated that the use of poles is slightly more economical than walking (Giovanelli et al. 2019).

In the outdoor test, our results also confirm what we have already reported (Giovanelli et al. 2022b). Indeed, the cardiorespiratory parameters did not differ between PW and W at either maximal or submaximal effort. This result is of great importance for athletes who participate in uphill races since they are faster with the same metabolic request when they use poles. The redistribution of force between the lower and upper limbs did not affect energy expenditure or RPE. Despite the lower mechanical efficiency of the arms compared to legs, studies using arm and leg ergometry have shown that redistribution of workload between the upper and lower limbs for a given oxygen uptake could improve performance by extending exercise duration (Bergh et al. 1976). In more complex movements, such as cross-country skiing, greater involvement of the arms in propulsion may reduce the cost of locomotion compared to relying mainly on legs work (Hoffman and Clifford 1990). Further investigation, including the measurement of muscle activation and workload of the upper and lower body when using poles, should be conducted to clarify why the contribution of less efficient muscle mass leads to improved performance without detrimental effects on the cost of locomotion.

Here it is worth emphasizing that participants were faster with the same energy expenditure during the maximal test with poles. It should also be noted that the use of poles in our study enhanced performance (i.e. decreased time to complete the same trail) during the maximal outdoor test but not during the maximal treadmill test. We speculated that this difference might be due to the different protocol of the two exercises. On the treadmill, participants performed the test by increasing the intensity every minute, whereas outdoor they had to express a maximum steady-state effort for 150 m of elevation gain.

As previously reported (Giovanelli et al. 2019), we found differences in some biomechanical parameters during the treadmill test when subjects used poles. Indeed, in level pole walking at a fixed speed it has been demonstrated that the use of poles leads to an increase of cycle time and cycle length both in healthy adults (Hansen et al. 2008; Pellegrini et al. 2018) and in elderly and pathological subjects (Nardello et al. 2017). The longer step lengths in pole walking could be due to either the propulsive action exerted by the poles and/or to the longer time required to complete the arm swing (Pellegrini et al. 2018).

In contrast, in this investigation, there were no differences in cycle time measured outdoors. This is in line with the finding of (Daviaux et al. 2013), who tested runners on terrain that simulated trail running terrain and found no differences in cycle time during PW on flat, uphill and downhill. This discrepancy between treadmill and outdoor is likely due to the different types of surfaces. The smooth surface of the treadmill elicits a regular diagonal stride, and subjects are able to adapt their steps to their preferences. In contrast, on the trail subjects must adapt their steps to the uneven terrain. It has been shown that moving on uneven surface causes an increase in the variability of stride length by 22% for walking (Voloshina et al. 2013) and by 27% for running (Voloshina and Ferris 2015).

In the present study walking on the treadmill allowed subjects to perform a diagonal arm–leg technique for the duration of the test. However, during the outdoor test, the movements of the poles were not synchronized with the foot movements. This is demonstrated by the fact that poling cycle time was longer than foot cycle time. While walking on a trail, the poles must be placed at specific points, to avoid placing them on a rock for example, and this also may affect the arms-legs coordination. It is interesting to note that, on the trail, subjects on average placed the poles once for every two cycles of leg movements (i.e., one poling action per two strides, with a time coordination of 1:2 between pole and leg).

This observation suggests that participants preferred longer cycles for the upper limbs during PW. When there are no external constraints (i.e., terrain elements on the ground) and participants synchronized their arms and legs, they tend to lower their stride frequency and lengthen their strides rather than increasing their arm movement frequency. However, it should be noted that in both cases

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(with or without synchronization of the arms with the legs), the load on the feet decreased.

In addition, in the test performed on the trail, the gradient of the terrain and the longitudinal speed varied during the test. This could lead to a greater variability in gait parameters than on a treadmill and, consequently, make it difficult to detect differences between conditions.

We decided to conduct this study by evaluating the parameters of interest in two different scenarios: on the treadmill and on a typical trail running path. On the one hand, the use of the treadmill allowed us to accurately set the speed and incline for the necessary duration to acquire enough consecutive steps. Further, this allowed measurements at different gradients and thus intensities. The speed of 1.1 m/s, which is slower than the walk/run transition speed in the range of inclines we studied, was chosen to induce the subjects to walk rather than run (Brill and Kram 2021). We decided to increase the gradient instead of the speed, not only to prevent the subject from transitioning to running but also because it has been reported that during diagonal stride in cross-country skiing, axial pole forces increase on steeper gradients but not at faster speeds (Pellegrini et al. 2011). The starting gradient and the increase in incline were chosen to maximise the subjects' performance on inclines similar to those chosen for the outdoor test. Finally, the incremental treadmill test allowed calculation of individual vertical velocity for the submaximal test outdoor.

A limitation of using the treadmill is that subjects found it uncomfortable when the gradient was steep and the feet and calves were stretched more than usual. Indeed, the RPE value on a steep treadmill is higher than the RPE value measured during walking on a trail of same incline and at the same speed (Giovanelli et al. 2022a). In our analysis, we reported the data up to a gradient of 20°, which is the stage that all subjects completed. Even though the outdoor investigation did not guarantee a perfectly controlled speed and locomotion pattern, it allowed us to evaluate the effect of the poles in an ecological scenario. Another limitation of our study is that we collected Ffoot and Fpole in only one direction and the force vector of the insole was different from the force vector of the poles. For this reason, the decrease of ΔFfoot on treadmill is not equal to the value of Fpole. Future research should use devices with 3 axial force sensors to measure both Fpole and Ffoot. Finally, measurements of muscle activation or other parameters related to the fatigue of the lower limbs should be performed to prove with absolute certainty that the use of poles allows to save energy on the lower limbs.

Practical applications

Based on the results of this study, we conclude that the use AQ2 of poles allows redistribution of force between the upper and lower limbs. Although there was no improvement in performance on the treadmill, the results of the outdoor investigation suggest that the use of poles allows athletes to climb faster and to apply less force with the lower limbs during both maximal and submaximal uphill efforts. These new results, combined with previous findings that the use of poles improves performance without increasing energy expenditure, suggest that the use of poles for trail runners is beneficial in maximal performance and in decreasing the force expressed by the lower limbs.

Conclusions

In summary, during both treadmill and outdoor effort at different intensities, inclines and speeds, we found that the use of poles leads to a reduction in foot force. Furthermore, during walking on steeper gradient an increased poling force AQ3 reduces the foot force and that could be beneficial for performance with no additional oxygen cost. Thus, it is reasonable to conclude that poles do "save the legs" when walking uphill at different intensities.

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Declarations

Conflict of interest The authors have no conflict of interest to declare.

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