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ORIGINAL ARTICLE

Do poles save energy during steep uphill walking?

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Abstract

Purpose In trail running and in uphill races many athletes use poles. However, there are few data about pole walking on steep uphill. The aim of this study was to compare the energy expenditure during uphill walking with (PW) and without (W) poles at different slopes.

Methods Fourteen mountain running athletes walked on a treadmill in two conditions (PW and W) for 5 min at seven different angles (10.1°, 15.5°, 19.8°, 25.4°, 29.8°, 35.5° and 38.9°). We measured cardiorespiratory parameters, blood lactate concentration (BLa) and rating of perceived exertion (RPE). Then, we calculated the vertical cost of transport (CoT_{vert}). Using video analysis, we measured stride frequency (SF) and stride length (SL).

Results Compared to W, CoT_{vert} during PW was lower at 25.4°, 29.8° and 35.5° PW (− 2.55 ± 3.97%; − 2.79 ± 3.88% and − 2.00 ± 3.41%, $p < 0.05$). RPE was significantly lower during PW at 15.5°, 19.8°, 29.8°, 35.5° and 38.9° (− 14.4 ± 18.3%; − 16.2 ± 15.2%; − 16.6 ± 16.9%; − 17.9 ± 18.7% and − 18.5 ± 17.8%, $p < 0.01$). There was no effect of pole use on BLa. However, BLa was numerically lower with poles at every incline except for 10.1°. On average, SF for PW was lower than for W (− 6.7 ± 5.8%, $p = 0.006$) and SL was longer in PW than in W (+ 8.6 ± 4.5%, $p = 0.008$).

Conclusions PW on steep inclines was only slightly more economical than W, but the substantially lower RPE during PW suggests that poles may delay fatigue effects during a prolonged effort. We advocate for the use of poles during steep uphill walking, although the energetic savings are small.

Keywords Energetics · Vertical km · Trail running · Pole walking

Introduction

In trail running, and in particular in vertical kilometer (VK) running races, many athletes use poles with the belief that they enhance their performance. However, based on the existing scientific literature for level walking, we would predict that using poles would negatively affect VK performance. Indeed, several studies reported that walking with poles (PW) on level terrain is more energetically demanding than conventional walking (W) (Saunders et al. 2008; Hansen and Smith 2009; Pellegrini et al. 2015; Church et al. 2002; Porcari et al. 1997; Schiffer et al. 2006). Submaximal oxygen uptake ($\dot{V}O_2$), heart rate (HR) and blood lactate concentration (BLa) are higher during PW than W compared at the same velocity on level terrain (Schiffer et al. 2006; Sugiyama et al. 2013; Hansen and Smith 2009; Pellegrini et al. 2015). Specifically, energy expenditure at a given velocity is ~ 20% greater when walking with poles (Church et al. 2002; Porcari et al. 1997; Schiffer et al. 2006). However, Pellegrini et al. (2015) and Hansen and Smith (2009) reported that the difference in energy expenditure between PW and W decreases on steeper inclines. This could lead to an energetic advantage for using poles when the slope is steeper than the inclines used in previous studies (12°) (Hansen and Smith 2009). Tantalizingly, Jacobson and Wright (1998) studied very steep (40°) uphill walking on outdoor trails and found that the heart rate and rate of perceived exertion (RPE) were lower when using poles. However, they did not measure oxygen uptake and did not report the walking velocities. Other studies have also reported that RPE is lower when subjects

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use poles during uphill walking (Figard-Fabre et al. 2010) and this may be particularly important when the effort is prolonged and at high intensity (e.g., during a VK).

VK race courses can exceed 30° of incline. For example, the world VK record for men (28 min and 53 s) in the VK was set on a course with an inclination of 31.4° (Km Vertical de Fully, SUI). Our previous study reported that there is a range of angles (20.4°–35°) for which energy expenditure per vertical meter of ascent (J kg^{-1} m^{-1}) is minimized, for both walking and running (Giovanelli et al. 2016). At a fixed vertical velocity (0.35 m/s) walking was always less metabolically expensive than running when the slope is steeper than ~ 10°. However, in that study and in other studies of steep uphill walking (Minetti et al. 2002; Ortiz et al. 2017) the subjects did not use poles. Noting that poles are commonly used during the VK races, Ortiz et al. (2017) suggested that measuring the metabolic effects of using poles during uphill walking is a logical next experiment.

Following that suggestion, the aim of the present study was to compare the energy expenditure during uphill walking with (PW) and without (W) poles at different slopes. We aimed to explore this field because the literature lacks information about the advantage that poles may lead during steep uphill races. Moreover, the available data about Nordic walking are not specific enough even though they provide some information and rationale to assume that the use of poles should be suggested on steep uphill. In fact, our hypothesis, based on the results of Pellegrini et al. (2015) and Hansen and Smith (2009), was that on steep slopes (above ~ 20°) the use of poles will be energetically advantageous. We also compared the stride frequencies and stride lengths during W and PW. We expected lower stride frequencies and longer stride lengths during PW compared with W (Zoffoli et al. 2016; Knight and Caldwell 2000).

Methods

Participants

Fourteen mountain running athletes, experienced with using poles participated in the study (Table 1). They all provided informed consent. The Institutional Review Board of the University of Udine approved the study protocol (22/IRB_Lazzer_18) and it was conducted according to the ethical standards of the Helsinki Declaration.

Experimental design

All the tests were performed in the exercise physiology laboratory of the University of Udine. Athletes visited the laboratory on three different days separated by at least 72 h. During the first visit, we collected anthropometric data and the athletes performed an uphill graded exercise test in which the incline and treadmill velocity were adjusted to increase the vertical velocity by ~ 120 m_{vert}/h (2 m_{vert}/min) every minute. We custom-built a metal frame that allowed us to incline a commercial treadmill (Technogym Excite 500, Cesena, Italy) up to ~ 40°. We replaced the original belt with a wider one (65 cm), a corrugated silicon-made belt normally used for industrial transport, which accommodated pole walking. The treadmill motor provided active resistance to the sliding of the belt during steep walking. Prior to the study began and during some pilot tests, we calibrated the treadmill velocity using a high-speed video camera (Nikon J1, Japan) at 400 Hz and Kinovea software (0.8.15; https://www.kinovea.com). We marked a line at a specific point on the treadmill belt. Then, from the belt length and rotation, we calculated the velocity (r^2 = 0.99). Also, we calibrated the angle using a digital level (Stanley Fatmax 120 cm, USA), and we double-checked the angle by analyzing video images with Kinovea.

Table 1 Anthropometric characteristics and training status of the participants

	Mean ± SD
Age (years)	32.7 ± 6.6
Body mass (kg)	67.4 ± 6.9
Stature (m)	1.76 ± 0.07
$\dot{V}O_{2max}$ (ml/kg/min)	73.7 ± 8.7
$V_{vert\ max}$ (m/s)	0.53 ± 0.06
Training status h/week (hh:mm)	08:08 ± 02:16
Elevation gain (m/week)	3514 ± 296
Best time on vertical kilometer (hh:min:s)	00:39:55 ± 00:05:08

Values are expressed as mean ± standard deviation (SD)

$\dot{V}O_{2\,max}$ maximal oxygen uptake, $V_{vert\ max}$ maximal vertical velocity during $\dot{V}O_{2max}$ testing

To familiarize the subjects with the equipment, they walked with and without poles for 3–5 min at each of seven different treadmill inclines (10.1°, 15.5°, 19.8°, 25.4°, 29.8°, 35.5° and 38.9°). The treadmill velocity was adjusted to maintain the vertical velocity equal to 80% of the vertical velocity corresponding to each individual's respiratory compensation point determined during the incremental test (Beaver et al. 1986). The average velocities of the treadmill used for the evaluations were 1.99 ± 0.24, 1.31 ± 0.16, 1.03 ± 0.16, 0.82 ± 0.10, 0.70 ± 0.08, 0.60 ± 0.07 and 0.56 ± 0.07 m/s for the respective inclines. However, at 10.1°, the treadmill belt velocity was too fast for some participants and only eight subjects were able to complete the trial with a RER lower than 1.00.

During the second and third visits, the order of walking with or without poles was randomly assigned. While blinded the subjects drew cards that indicated the slopes and conditions. Afterwards, they performed the trials in the order prescribed by the cards. Then, participants performed half of the trials on day 2 and the other half on day 3. Athletes were allowed to rest for 5 min between trials.

Pole length and pole walking technique

The pole length was determined by multiplying the subject's height in cm by 0.68, in accordance to the study of Pellegrini et al. (2015) and similar to "self-selected pole length" reported by Hansen and Smith (2009) (67 ± 0.6% of the subjects' height). However, subjects were allowed to change the pole length after the familiarization. At the steep slopes, the length proposed by previous studies was too long and uncomfortable for some athletes. The average preferred pole length was 58 ± 0.02% of the subject's height (range 55–63%). Subjects were instructed to walk with a diagonal technique that consists of alternately moving opposite arms and legs [for details see International Nordic Walking Association (INWA 2017) and Pellegrini et al. (2018)].

Metabolic measurements

During the test, subjects wore a portable metabolimeter (K5, Cosmed, Italy) and we measured the $\dot{V}O_{2f}$ and $\dot{V}CO_2$ during the entire 5-min trial. Before every test, we calibrated the volume and gas analyzers using a 3-l calibration syringe and calibration gas (16.0% O_2; 5.0% CO_2), as suggested by the manufacturer. We averaged the data of the last 2 min of each trial and calculated metabolic power (in W/kg) using the equation proposed by Peronnet and Massicotte (1991). We calculated the vertical cost of walking with and without poles (J kg^{-1} m^{-1}) by dividing the gross metabolic power by vertical velocity. We analyzed only the data in which the subject's RER was less than 1.0. Moreover, in order to determine if there was any slow component in the $\dot{V}O_2$ kinetics, we averaged the metabolic power of min 4 and min 5 separately, and we compared those data for all the trials (Ortiz et al. 2017). Between 30 and 60 s after the finish of the trials, we collected mixed venous blood at the earlobe and measured the BLa with a dedicated device (Bionsen C-line GP+, EFK diagnostic, Cardiff, UK). Before every test, we calibrated the lactate device by using a calibration test-tube provided by the manufacturer.

Perceived exertion

During the last minute of each PW or W trial, we asked the subjects to evaluate their overall perceived exertion by using the Borg CR-10 Scale with the 0 value meaning "nothing at all" and 10 value meaning "extremely hard" (Borg 1998).

Biomechanical parameters

We measured the stride parameters for 10 successive strides using a high-speed video camera (Nikon J1, Japan) at 400 Hz. We measured contact time using Kinovea software and then calculated stride frequency (SF = 1/stride time) and stride length (SL = velocity/stride). Contact times started when the foot visibly contacted the treadmill and ended when it took off.

Statistical analysis

We analyzed the data using GraphPad Prism 7.0 with significance set at $p \leq 0.05$. We compared the vertical cost of walking with and without poles, and biomechanical parameters with a general linear model (2-way ANOVA) for repeated measures considering two factors (slope and poles: walking with poles vs. walking without poles). When significant differences were detected, we applied the Sidak post hoc test (provided by the statistics software) to identify which conditions were significantly different. For the vertical cost of transport, rate of perceive exertion, blood lactate concentration, stride frequency and stride length, we performed a second-order polynomial regression to fit the curve for walking (dashed line) and pole walking (continuous line). The curve fitting was performed considering all the points (one point = one subject) and not the average values for every incline.

Results

Vertical cost of transport

The statistical analyses revealed that there was a main effect of using poles on CoT_{vert} when W and PW were compared ($p = 0.002$). However, comparing the results at each incline between the two conditions, we found that there were no significant differences in CoT_{vert} at 10.1°, 15.5°, 19.8° and 38.9° ($p > 0.05$). However, at 25.4°, 29.8° and 35.5°, PW was less demanding than W (− 2.6 ± 4.0%, $p = 0.028$; − 2.8 ± 3.9%, $p = 0.019$ and − 2.0 ± 3.4%, $p = 0.048$, respectively) (Fig. 1).

CoT_{vert} of W was numerically least at 19.8° (56.9 ± 7.87 J kg^{-1} m^{-1}), but it was not statistically different from 15.5° (58.6 ± 7.84 J kg^{-1} m^{-1}, $p = 0.137$) or 25.4° (58.5 ± 7.51 J kg^{-1} m^{-1}, $p = 0.123$).

CoT_{vert} of PW was also numerically least at 19.8° (56.2 ± 7.42 J kg^{-1} m^{-1}), but it was not statistically different from 15.5° (57.6 ± 6.45 J kg^{-1} m^{-1}, $p = 0.207$) or 25.4° (57.1 ± 7.98 J kg^{-1} m^{-1}, $p = 0.421$).

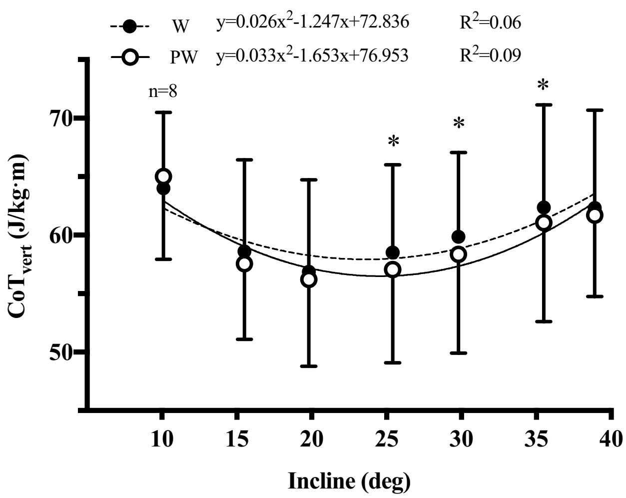

Fig. 1 Vertical cost of transport (CoT_{vert}, J kg^{-1} m^{-1}) of walking (filled circle) and pole walking (open circle) plotted as a function of angle (degrees) for 14 subjects. At 10.1°, data for only eight subjects could be obtained. All values are expressed as means ± SD. *Significance of $p<0.05$ between W and PW

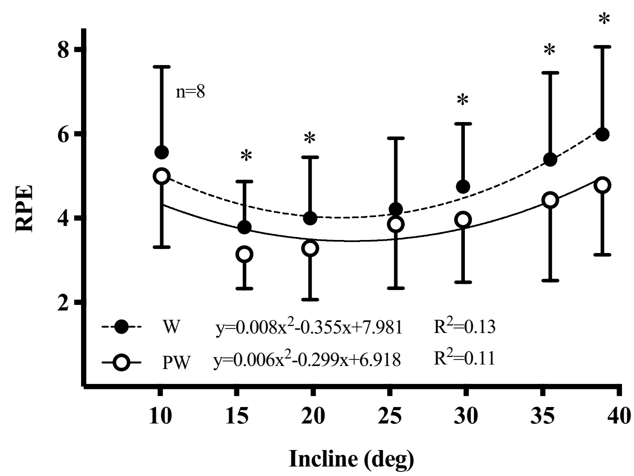

Fig. 2 Rate of perceived exertion (RPE) of walking (filled circle) and pole walking (open circle) plotted as a function of angle (degrees) for 14 subjects. At 10.1°, data for only eight subjects could be obtained. All values are expressed as means ± SD. *Significance of $p<0.05$ between W and PW

Heart rate, ventilation and tidal volume

There were no differences in heart rate ($p=0.16$) or tidal volume ($p=0.88$) between W and PW at any of the analyzed slopes. Minute ventilation ($\dot{V}$E) was numerically lower during PW at every incline except for 10.1°, but still not significantly different (on average − 2.7 ± 3.0%, $p=0.17$).

Rating of perceived exertion

A main effect of pole use on RPE appeared when W and PW were compared ($p<0.001$). The RPE values were lower in PW than in W at every incline. However, at 10.1° and at 25.4°, the difference was not statistically significant (− 9.2 ± 11.8%, $p=0.094$ and − 7.3 ± 14.3%, $p=0.086$, respectively). At all the other inclines, the RPE was significantly lower in PW (− 14.4 ± 18.3, $p=0.002$ at 15.5°; − 16.2 ± 15.2, $p=0.002$ at 19.8°, − 16.6 ± 16.9%, $p=0.005$ at 29.8°; − 17.9 ± 18.7%, $p=0.007$ at 35.5° and − 18.5 ± 17.8%, $p=0.001$ at 38.9°) (Fig. 2). RPE during W was numerically least at 15.5° (3.8 ± 1.09), but it was not statistically different from 19.8° 4.0 ± 1.44, $p=0.396$) and 25.4° (4.2 ± 1.68, $p=0.310$). RPE of PW was also numerically least at 15.5° (3.1 ± 0.82), but it was not statistically different from 19.8° (3.3 ± 1.22, $p=0.435$).

Blood lactate concentration (BLa)

The statistical analyses revealed no effect of pole use on BLa when W and PW were compared ($p=0.092$). However, BLa was numerically lower at every incline except for 10.1° (average − 7.3 ± 17.4%) (Fig. 3). BLa during W was numerically least at 19.8° (2.6 ± 1.3 mmol/L), but it was not statistically different from 15.5° (3.1 ± 1.8, $p=0.182$). Conversely, at 10.1°, 25.4°, 29.8°, 35.5° and 38.9°, BLa were greater than at 15.5° (4.1 ± 1.31, 3.2 ± 1.4, 3.6 ± 1.4, 4.6 ± 2.0 and 5.2 ± 1.8 mmol/L, $p>0.05$, respectively). BLa during PW was numerically least at 19.8° (2.6 ± 1.3 mmol/L), but it was not statistically different from 15.5° (3.1 ± 1.8, $p=0.182$). Conversely, at 10.1°, 25.4°, 29.8°, 35.5° and 38.9° BLa was higher than at 19.8° (4.1 ± 1.31, 3.2 ± 1.4, 3.6 ± 1.4, 4.6 ± 2.0 and 5.2 ± 1.8 mmol/L, $p>0.05$, respectively). BLa during W

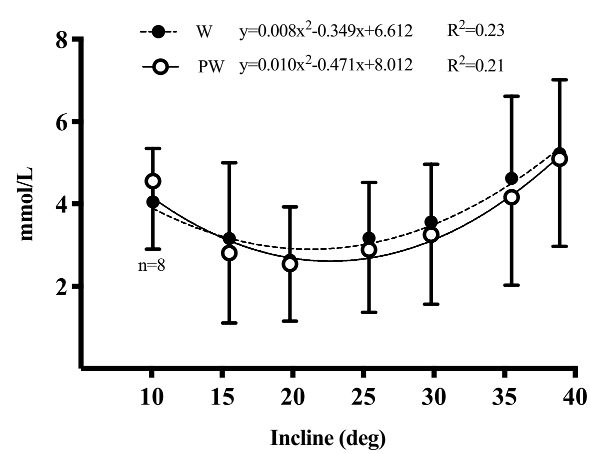

Fig. 3 Blood lactate concentration (mmol/L) for walking (filled circle) and pole walking (open circle) plotted as a function of angle (degrees) for 14 subjects. At 10.1°, data for only eight subjects could be obtained. All values are expressed as means ± SD

was numerically least at 19.8° (2.5 ± 1.3 mmol/L), but it was not statistically different from 15.5° (2.8 ± 1.7, $p = 0.406$). Conversely, at 10.1, 25.4, 29.8, 35.5 and 38.9° BLa was higher than at 19.8° (4.5 ± 1.6, 2.8 ± 1.7, 2.9 ± 1.5, 3.2 ± 1.7 and 5.1 ± 2.1 mmol/L, $p > 0.05$, respectively).

Stride kinematics

SF for PW was lower than for W (average − 6.7 ± 5.8%, $p = 0.006$). However, at 10.1, 35.5 and 38.9° there were no statistical differences. Consequently, since the treadmill velocity was the same between conditions, SL was longer during PW than during W (average + 8.6 ± 4.5%, $p = 0.008$). In both W and PW conditions, because we maintained the same vertical velocity, treadmill belt velocity was slower on steeper inclines and thus SF and SL decreased on steeper inclines (Fig. 4a, b).

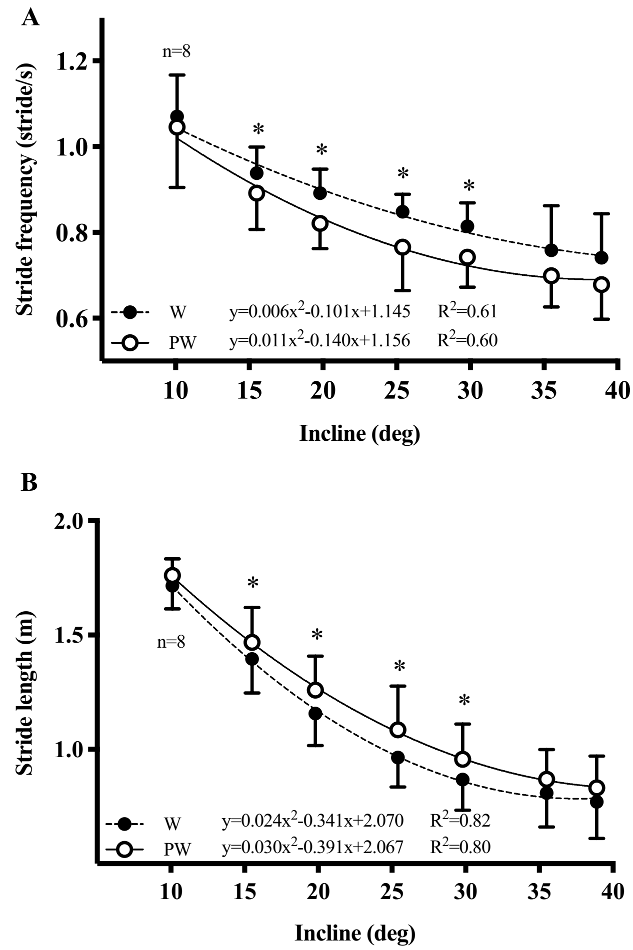

Fig. 4 Stride frequency (**a**) and stride length (**b**) of walking (filled circle) and pole walking (open circle) plotted as a function of angle (degrees) for 14 subjects. At 10.1°, data for only eight subjects could be obtained. All values are expressed as means ± SD. *Significance of $p < 0.05$ between W and PW

Discussion

We found that: (1) walking with poles on steep inclines was slightly more economical than walking without poles; (2) walking with poles elicited lower RPE than walking without poles and (3) using poles results in lower stride frequencies and longer stride lengths.

We accept our hypothesis that walking with poles is energetically advantageous on inclines steeper than 20°. Previous studies have found that, on level terrain, the $\dot{V}O_2$ when using poles was between ~ 20 and ~ 40% greater than walking without poles (Pellegrini et al. 2015; Hansen and Smith 2009), but this difference was less during uphill walking. The same studies reported that on 8.5° and 12° inclines, $\dot{V}O_2$ when using poles was only ~ 7% greater than not using poles. From the extrapolation of the data from those two studies, we expected to find a "cross-over" point at which walking with poles would be more economical than conventional walking. Numerically, we found this cross-over point at ~ 15° of incline. That is, when the slope is steeper than 15°, it is energetically advantageous to use poles. In the present study, the difference was statistically different at and beyond 25.5°, but the metabolic savings (average − 2.5%) were less than we expected. Note that at 10.1° the vertical cost of transport during PW was numerically greater than W. But, at 10.1°, only eight subjects were able to finish the trial with a RER lower than 1.0 and for some athletes the velocity (> 2.22 m/s) was faster than their natural walk–run transition velocity on level terrain (di Prampero 1986; Hreljac et al. 2007). Since at this incline/velocity (~ 10° and ~ 2 m/s) running is more economical than walking (Giovanelli et al. 2016) and usually athletes do not use poles while running, we advise against their use in this condition. However, it is not yet known if running with poles is advantageous or not. Further experiments could explore this topic.

On level terrain, the increased metabolic cost in PW has been ascribed to the higher demand of the upper extremity muscles (Knight and Caldwell 2000). Unlike during race conditions, Nordic walking is a practice that intentionally aims to increase the metabolic demand. Indeed, participants may exaggerate the movements of upper limbs to reach a higher energy cost (e.g., for losing weight). In contrast, race performance should be positively affected by a lower energy cost of transport. During steep uphill walking with poles, the reduced leg muscle activity (Foissac et al. 2008) may lead to a lower perceived exertion. During long-duration events, using the arms for performing mechanical work against gravity may help to reduce fatigue in legs. Indeed, when subjects are allowed to use arms for contributing in the total mechanical work during a purely concentric effort (i.e., cycling/arm-cycling or uphill walking), the power exerted is greater than the power reached with the only use of legs (Nagle et al. 1984; Hill et al. 2018). Thus, at the same power output, subjects may experience less fatigue in their legs. Hence, the lower cost of transport during PW may derive from a better distribution of work between lower and upper limbs. However, we can only speculate that a better distribution leads to lower energy expenditure, since we do not have data about EMG and propulsion force with arms.

The present study supports our previous findings that there is a range of optimal inclines during uphill walking or running (Giovanelli et al. 2016). With poles we found that the vertical ascent rate may be maximized in a range of slopes between ~ 15° and ~ 25°. Hence, athletes who want to achieve their best uphill performances should race on these slopes.

In our study, RPE was lower when the subjects used poles. This agrees with previous studies in which authors reported lower or unchanged RPE when subjects used poles despite an increase in energy expenditure (Figard-Fabre et al. 2010; Jacobson and Wright 1998; Church et al. 2002; Duncan and Lyons 2008; Perrey and Fabre 2008; Grainer et al. 2017). In particular, Figard-Fabre et al. (2010) reported lower RPE during uphill PW at + 2.8° compared to W up the same incline. Collectively, these studies suggest that when subjects are walking with poles they experience less fatigue despite their greater energy expenditure. During a short-lasting effort, fatigue may be of little interest, but during a prolonged exercise (e.g., VK race or during a trail running race) the effect could be greater and more important. Interestingly, Knight and Caldwell (2000) compared W and PW during a protracted uphill trial (1 h at 5° of incline with a backpack). They reported that RPE was lower during pole walking throughout the test session despite a time-dependent increase in RPE under both conditions. They also reported the presence of a slow component in HR during W that may accelerate the onset on fatigue effects. Since VK races last 30–60 min and fatigue plays an important role in determining final performance, it would be interesting to study the use of poles for a similar duration on a 30° incline which is typical of the most important VK races around the world [see Giovanelli et al. (2016) for more details]. However, during pilot experiments, we found that at inclines > 20° it was not possible to walk for more than 8–10 min without suffering pain in the legs and feet due to the excessive hyperflexion of the ankle at such steep inclines. Conversely, during outdoors performance the continuous changes in surface characteristics allow adjustments in the foot support that avoid excessive and repeated stress on the feet and legs.

In contrast to Schiffer et al. (2006), we did not find differences in BLa between W and PW. Schiffer et al. (2006) reported higher level of lactate in PW than in W at different velocities and they attribute this to the work exerted by the upper torso musculature. The different protocol used in our study may explain this discrepancy. To our knowledge there are no other studies of lactate accumulation in PW or W, but Hoffman et al. (1996) described a slightly lower BLa when subjects combined arm and leg exercise vs. purely leg exercise at the same combined power output. It may be that during PW on steep inclines, the involvement of upper body muscles promote the reuptake and utilization of lactate (Gladden 2004). The relative intensity of the PW and W tests was ~ 83% of $\dot{V}O_{2max}$ and therefore assumingly lower than lactate threshold, suggesting that the energy demand were covered by net aerobic energy turnover.

We accept the hypothesis that using the poles affects stride kinematics. Indeed, as previously reported (Zoffoli et al. 2016; Knight and Caldwell 2000), we found lower SF accompanied by longer SL (Willson et al. 2001) when the subjects used poles. SF and SL decreased on steeper inclines in part due to the slower treadmill velocities. We do not have information about the ground reaction forces during PW and W and we do not know if the use of poles reduces the forces applied on the lower extremities as happens during downhill PW (Schwameder et al. 1999). Since subjects were allowed to self-select the workload distribution between upper and lower limbs, we can only assume that they used the most economical technique (Hoffman et al. 1996; Hill et al. 2018).

We acknowledge that our study had some limitations. These results may be not entirely applicable to outdoor walking on real trails. Indeed, we asked the subjects to perform a diagonal arm–leg technique during all the trials. However, in field conditions, the uneven terrain may require a different pattern of movement (e.g., double poling) with different metabolic demands. Also the difference between the smooth belt and the uneven terrain may affect the results (Voloshina and Ferris 2015). Second, since we did not have instrumented poles we do not know the magnitude of forces exerted by the participants during the pushing phase. Indeed, as reported by Pellegrini et al. (2018), different pushing patterns may elicit different metabolic demand. Although the subjects enrolled in this study were expert pole users, they might have used different pushing patterns.

In conclusion, we advocate for the use of poles during steep uphill walking, although the energetic savings with poles were small. Our results, combined with those of previous studies, suggest that the use of poles may delay local fatigue effects during a prolonged effort (e.g., VK or trail running races). However, the use of poles for optimizing race performance requires learning the proper technique and training the upper body musculature.

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Author contributions NG, RK and SL conception and design of research; NG and MS conducted experiments and analyzed data; NG, RK and SL interpreted results of experiments; NG and MS prepared figures; NG drafted manuscript; NG, MS, RK and SL edited and revised manuscript. NG, MS, RK and SL approved final version of manuscript.

Compliance with ethical standards

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

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