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ORIGINAL ARTICLE

The impact of pole use on vertical cost of transport and foot force during uphill treadmill walking before and after a simulated trail running competition

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Abstract

Purpose Trail running poles are widely used among trail runners but their effects on cost of transport and biomechanics under fatigued conditions remains understudied. This study aimed to evaluate the effects of pole use on the walking vertical cost of transport (CoT_{vert}) and foot force (FF) before and after a simulated trail running competition (STRC).

Methods Sixteen trail runners ($\dot{V}O_2$: 61.0 ± 8.3 ml/kg/min; ITRA performance index: 634 ± 107 points) performed walking trials with (PW) and without poles (CW) on an incline treadmill (18.6 degrees) before (PRE) and after (POST) a STRC. The course covered 31.2 km with 2086 m of elevation gain and was completed under race-simulated conditions. CoT_{vert} and FF were measured using instrumented insoles, and axial pole force was recorded during PW.

Results The STRC was completed in 4:25:33 ± 0:39:51 (hh:mm:ss) at an average heart rate (HR) of 81.4 ± 3.8% of HRmax. Walking CoT_{vert} showed significant *time* and *condition* effects, with higher values without poles at POST (+2.50 ± 2.62%, $p = 0.0183$). Rating of perceived exertion (RPE) was lower with poles at both PRE and POST ($p = 0.0022$ and $p = 0.0187$, respectively). FF was significantly lower with poles at PRE ($p = 0.0140$) and POST ($p < 0.0001$). Poling force decreased at POST compared to PRE ($p = 0.0026$).

Conclusions The main findings are that (1) CoT_{vert} increases after STRC; (2) walking CoT_{vert} and FF are lower with pole use and (3) upper limb force decreases at POST. These results support the use of poles in long-lasting events to reduce CoT, redistribute workload and possibly mitigate the fatigue effects.

Keywords Trail running · Training · Mountain running · Pole walking · Cost of transport

Abbreviations

[BLa]	Blood lactate concentration
CHO	Carbohydrates
CoT	Cost of transport
CoT_{vert}	Vertical cost of transport
CW	Conventional walking
EIMD	Exercise-induced muscle damage
FF	Foot force
fTcont	Foot contact time
GET	Gas exchange threshold
HR	Heart rate
peakLRF	Maximal value for loading rate for foot
peakLRP	Maximal value for loading rate for pole
PF	Poling force
pTcont	Pole contact time
PW	Pole walking
RCP	Respiratory compensation point
RPE	Rating of perceived exertion
RQ	Respiratory quotient
SF	Stride frequency
STRC	Simulated trail running competition
$\dot{V}CO_2$	Carbon dioxide production
VE	Ventilation

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$\dot{V}O_{22}$ Oxygen uptake
v_{vert} Vertical velocity

Introduction

Trail running poles are widely used among trail runners, with the general belief that they may help save energy and enhance performance by assisting athletes in lifting their centre of mass, thereby reducing the work required against gravity. Indeed, since the vertical cost of transport (CoT_{vert}) is one of the primary determinants of trail running performance (Ehrstrom et al. 2018), athletes should adopt strategies to minimize it. In one study, we found that poles allow for a small reduction in metabolic energy expenditure during steep (> 20 degrees) treadmill pole walking (Giovanelli et al. 2019). In this study, we reported that at submaximal intensities (80% of the vertical velocity (v_{vert}) corresponding to respiratory compensation point (RCP)), CoT was lower when participants used poles, suggesting that pole use should be encouraged. However, in a real-world scenario, we found that during a short, all-out effort (150 m of elevation gain performed at ~ 85% of maximal oxygen uptake ($\dot{V}O_{2max}$)), the use of the poles improved uphill performance (i.e., reduced the time to complete the ascent) without affecting CoT. Similar results were observed during a submaximal effort (~ 67% of $\dot{V}O_{2max}$), where no difference in CoT was found between using or not using poles on an uphill mountain path (Giovanelli et al. 2022, 2023). The discrepancy between these findings may be attributed to differences in experimental design (treadmill versus overground), even though the trials were conducted at similar intensity (~ 80% of the vertical velocity at the RCP). Additionally, unlike in typical trail running competitions, where participants are often in a fatigued state, the subjects in these studies were tested starting from a rested state.

As previously reported and reviewed (Millet et al. 2011; Giandolini et al. 2016), trail running competitions lead to a decrease in lower limb muscle strength. This loss of force can be attributed to impairments in neuromuscular function (Saugy et al. 2013; Martin et al. 2010) and exercise-induced muscle damage (EIMD) caused by repeated downhill sections (Giovanelli et al. 2021; Howatson et al. 2011). Furthermore, CoT can change following a trail running race, although the effects of such exercise remain unclear (Vernillo et al. 2017) and studies have reported differing results between "short" and "long" races, partly due to variations in the type of effort required (Sabater Pastor et al. 2021). Nevertheless, EIMD and the resulting force loss in lower limbs may encourage athletes to engage the upper limbs more, such as by using poles during uphill sections over prolonged periods. This strategy could allow the work required to lift the body to be shared between the upper and lower limbs. However, the involvement of the upper limbs in a fatigued state has not been previously tested. Indeed, in all prior studies, the effects of pole use on CoT were not evaluated under fatigued conditions, which are common after several hours of competition.

The purpose of this study was to assess the effects of using poles before and after a simulated trail running competition (STRC) covering 31.2 km with 2086 m of elevation gain on: (a) the vertical cost of transport (CoT_{vert}) and (b) on the force exerted through the feet. We hypothesized that after the test the CoT_{vert} of pole walking (PW) would be lower than that of conventional walking (CW) but higher than before the exercise. In addition, since the lower limbs were repeatedly engaged in eccentric contractions, we expected that after the test, the involvement of the upper limbs would increase (i.e., higher relative force would be applied to the poles) lowering the force exerted through the feet.

Methods

Participants

We enrolled 16 experienced male trail runners (age: 38.9 ± 7.2 years; body mass: 70.5 ± 5.5 kg; height: 1,78 ± 0.04 m; ITRA performance index: 634 ± 107 points), expert in using poles (Table 1). Based on the study by (Vernillo et al. 2014) we calculated that the minimum sample size for obtaining a statistical power of 80% with an alfa error of 0.05 was 12 subjects. However, we included additional participants to account for potential dropouts or technical errors during data collection. All the participants 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 64/2021).

Experimental design

The study comprised two test sessions conducted on separate days. Each session was scheduled in agreement with all participants, with the two sessions spaced 2–7 days apart. On Day 1, we collected the anthropometric data and conducted an uphill incremental test to exhaustion on treadmill. On Day 2, the participants completed walking trials with poles (PW) and without poles (i.e., conventional walking (CW)) on an incline treadmill before (PRE) and after (POST) a STRC covering 31.2 km with 2086 m of elevation gain. We instructed the participants to maintain an intensity comparable to that of a race with similar distance and elevation gain. During PRE and POST tests, we measured the cardiorespiratory parameters, CoT_{vert} of PW and CW, foot force

Table 1 Maximal, respiratory compensation point- (RCP) and gas exchange threshold- (GET) values of the participants identified during the incremental uphill test on treadmill

	Mean ± SD
Maximal values	
$\dot{V}O_{2max}$ (ml/kg/min)	61.0 ± 8.3
HR max (bpm)	178.6 ± 10.9
RQ max	1.13 ± 0.05
RPE max	19.6 ± 0.5
v_{vert} max (m/s)	0.50 ± 0.05
Respiratory compensation point	
$\dot{V}O_2$ (ml/kg/min)	53.4 ± 5.3
$\dot{V}O_2$ (%max)	81.3% ± 2.30%
HR (bpm)	165.8 ± 11.1
HR (%max)	92.7% ± 1.6%
RQ	1.02 ± 0.05
RPE	15.5 ± 1.1
v_{vert} (m/s)	0.37 ± 0.06
v_{vert} (%max)	81.1% ± 2.9%
Gas exchange threshold	
$\dot{V}O_2$ (ml/kg/min)	45.9 ± 7.6
$\dot{V}O_2$ (%max)	69.6% ± 6.0%
HR (bpm)	151.9 ± 10.2
HR (%max)	84.0% ± 2.6%
RQ	0.94 ± 0.03
RPE	13.5 ± 1.5
v_{vert} (m/s)	0.34 ± 0.04
v_{vert} (%max)	67.5% ± 3.6%

$\dot{V}O_2$ oxygen consumption; v_{vert} vertical velocity; *HR* heart rate; *RQ* respiratory quotient; *RPE*: rating of perceived exertion

and poling force. During the STRC we recorded heart rate, exercise time and rating of perceived exertion (RPE).

Incremental uphill test

Every participant completed an uphill incremental graded test on a treadmill (Skillrun, Technogym, Cesena, Italy) under medical supervision. This test was performed without poles, since there are no differences in maximal or submaximal parameters between an incremental test on treadmill with or without poles (Giovanelli et al. 2023). Participants were free to walk or run as they preferred. After a 5-min warm-up at a self-selected speed and slope, athletes started the test at the speed of 5 km/h and a slope of 10%. Every minute, an operator increased the slope by 2% until 24%. At this point, the slope was maintained at 24% and an operator increased the speed by 0.4 km/h until volitional exhaustion of the subject. This protocol allowed to increase the vertical velocity linearly by ~ 93 m/h every minute. During this test, we measured the ventilation (VE), the rates of oxygen uptake ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using a wearable metabolic unit (K5, Cosmed, Rome, Italy). In addition, we recorded HR with a dedicated device (Garmin HRM-run, Olathe, Kansas, USA). After the conclusion of the test we determined the respiratory compensation point (RCP) and the gas exchange threshold (GET) with the V-slope method (Beaver et al. 1986). Also, we determined the maximal parameters ($\dot{V}O_{2max}$, maximal heart rate (HRmax), maximal vertical velocity (v_{vert}max)). $\dot{V}O_{2max}$ was calculated as the average of the highest 30-s $\dot{V}O_2$ value, determined when the following criteria were met: (1) presence of a $\dot{V}O_2$ plateau during the final 1–2 min, (2) respiratory quotient (RQ) ≥ 1.1, and (3) achievement of ≥ 90% of theoretical HRmax (Howley et al. 1995). We calibrated the volume and gas analysers before every test as suggested by the manufacturer.

Cardiorespiratory values and cost of transport

We evaluated each participant on a customized treadmill before and within 5 min after a STRC. During testing, participants wore standard running attire (technical t-shirt, shirts, and trail running shoes). Each subject completed 2 5-min walking trials: 1 with poles and 1 without poles (in a randomized order between participants). In the PW condition, participants used length-adjustable aluminum poles (Inverso-Alu, Gabel, Rosà, Italy), set to the length typically used during their training and competitions (64.6 ± 1.4% of body height). The poles were equipped with force transducers (described below) and cross-country ski tips with tungsten carbide spikes to ensure proper treadmill traction. The total weight of each instrumented pole was 298 g. Participants were allowed to self-select their pole walking technique without restriction to specific movement patterns.

Between the two trials subjects rested 2 min (the time necessary to put/remove the equipment for the measurements). The exercise intensity for both pre- and post-tests was set at a v_{vert} corresponding to 80% of the v_{vert} at RCP as determined during the incremental test, maintaining a fixed incline of 18.6 degrees and adjusting the belt speed to reach the targeted v_{vert}. This specific incline was selected to ensure the belt speed remained below the walk–run transition threshold (Brill and Kram 2021), as faster speeds would have compromised proper pole usage.

We continuously measured $\dot{V}O_2$ and $\dot{V}CO_2$ throughout each trial, and then we averaged the data of the last minute. During all tests, we visually confirmed that a steady-state plateau had been achieved before terminating the test. Further, we calculated gross metabolic power (in W/kg) using the equation proposed by Peronnet and Massicotte (1991). Then, we calculated the vertical cost of transport (CoT_{vert}, in J/kg/m).

At the end of each bout we asked the subjects to rate their perceived exertion by using the Borg 6–20 Scale (Borg 1998). One minute after the end of the test, we collected mixed venous blood at the earlobe and measured the blood lactate concentration ([BLa]; Lactate Scout 4, EKF Diagnostic, Cardiff, UK).

Force measurements

During PRE and POST tests we measured the force applied through the foot by using instrumented insoles (Loadsol®, Novel, Munich, Germany). During pole walking we measured also the axial force applied on poles by a 15 g single-axial force transducer (Deltatech, Sogliano al Rubicone, Italy) inserted beneath each handgrip (Pellegrini et al. 2018). We acquired both foot and pole forces at 100 Hz. We obtained the data over the last minute on every side and calculated for every cycle the following parameters: foot force (FF), poling force (PF), stride and poling frequency, foot contact time (fTcont) and pole contact time (pTcont). Both FF and PF were calculated as the average force over the entire cycle. This calculation method, as opposed to averaging force over the contact time alone, allows for a more representative measure of the average force over the entire cycle, which includes both stance and swing phases. Peak loading rate for foot (peakLRF) and for pole (peakLRP) were calculated as the maximal value of the first derivative of foot force and pole force respectively. We extracted the parameters for each side and each cycle and then we averaged left and right side.

Trail running course and equipment

After the PRE measurements in the laboratory, participants completed a trail running course of 31.2 km with 2086 m of elevation gain (Fig. 1). Start and finish were placed at the laboratory and the course included 11% of pavement surface, 80% of mountain trail and 9% of gravel roads.

We asked to the participant to simulate their self-selected race pace (i.e., completing the course in the shortest time possible). Every participant had to carry with him the common equipment required during trail running races. In particular, they had a trail running vest in which they carried 2 flasks of 0.5 L, a waterproof jacket, a cell phone, some food and an emergency kit with plasters, tape and bandages. An operator followed the participants on an e-bike along the course where it was possible to ride. They were allowed to drink and to feed ad libitum. As well, they were not force to use the poles in a specific way, but as they felt comfortable.

Statistical analysis

We analyzed the data using GraphPad Prism 9.3.1 (GraphPad Software, San Diego, California, USA) with significance set at $p < 0.05$. We performed the ROUT method with a Q = 1% to detect any outliers in all parameters (Motulsky

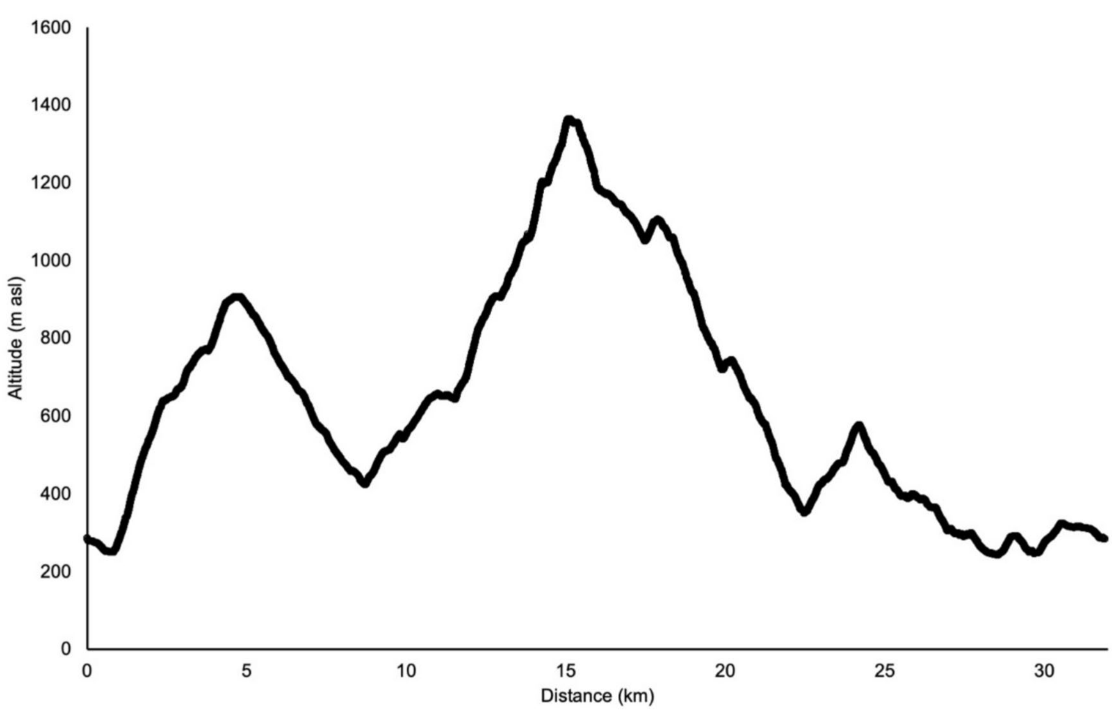

Fig. 1 Elevation profile of the simulated trail running competition

and Brown 2006). All identified outliers were excluded from the analysis for the affected parameter(s). We also verified that parameter values were normally distributed. Afterward, we compared with 2- way ANOVA the CoT_{vert}, RQ and RPE. For parameters with missing values (HR, FF-related parameters), we used a linear mixed-effects model (Type III F-test) with a random intercept for participants. Specifically, Prism performs a deviance analysis, interpreting the linear mixed-effects model analogously to an ANOVA.

For the 2-way ANOVA and linear mixed-effects model we considered two factors: *Time*: PRE and POST; *Condition*: PW and CW. When significant differences were detected, we applied the Tukey's post hoc test. We compared the poling-related parameters (poling force, poling frequency, pTcont, peakLRP) not available for W condition, with a paired two-tailed t test comparing PW PRE and PW post.

Due to a technical problem with the Cosmed K-5 device, we only obtained metabolic data for 15 out of 16 subjects during PRE and POST test. Also, due to a technical problem with the force cell installed in the poles we obtained the data for thirteen out of 16 tested subjects. Similar problems affected the foot-related parameters for which we could not process the data for four participants.

Results

Incremental test

The participants concluded the incremental test with a vertical velocity of 0.50 ± 0.05 m/s (corresponding to 1800 ± 178 m/h) and $\dot{V}O_2$ was 61.0 ± 8.3 ml/kg/min. RCP was identified at 0.37 ± 0.06 m/s of vertical velocity (corresponding to 1326 ± 226 m/h) (Table 1).

Simulated trail running competition

STRC was completed in 4:25:33 ± 0:39:51 (hh:mm:ss) with an average HR of 144.8 ± 11.1 bpm corresponding to 81.4 ± 3.8% of HRmax and 87.8 ± 4.2% of RCP measured during the incremental test. Average speed was 2.0 ± 0.03 m/s that corresponds to 8 min and 20 s per km. Participants reported an overall RPE of 15.5 ± 1.7. They lost − 2.7 ± 0.9 kg during the STRC (p < 0.0001), corresponding to − 3.9 ± 1.3% of their body mass.

Pre versus post simulated trail running competition

Poling technique

According to the pole force data, during the PW condition on the treadmill, participants primarily used diagonal techniques for pole movement patterns. Deviations from these techniques included the use of double-poling, which occurred in only 0.044 ± 0.063% of the cycles during the PRE condition and 0.063 ± 0.037% during the POST condition.

Vertical cost of transport and cardiorespiratory values

The two-way ANOVA revealed *time* and *condition* effect on CoT_{vert} (p = 0.0076; F (1.000, 14.00) = 9.690 and p = 0.0237; F (1.000, 14.00) = 6.437, respectively). Post hoc analysis indicated that CoT_{vert} at POST was higher without poles (+ 2.50 ± 2.62%, p = 0.0183). Also, the two-way ANOVA revealed *time* and *condition* effect on respiratory quotient (p < 0.0001; F (1.000, 14.00) = 50.34 and p = 0.0310; F (1.000, 14.00) = 5.749, respectively). A significant *time* effect was also observed for HR (p < 0.0001; F (1.000, 13.00) = 39.63). Furthermore, significant *time* (p = 0.0022; F (1.000, 9.000) = 17.90) and *condition* (p = 0.0187; F(1.000, 9.000) = 17.90) effects were found for RPE. Post hoc analysis revealed that RPE was significantly lower with poles both at PRE (p = 0.0436) and POST (p = 0.0157) (Fig. 2 and Table 2).

Foot- and poling- force related parameters

There was a *Condition* effect for FF (p < 0.0001; F(1.000, 11.000) = 45.81) that was lower with poles. Post-hoc analysis revealed that at PRE and POST, FF was lower when using poles by − 4.2 ± 3.3% (p = 0.0140) and − 4.1 ± 1.5% (p < 0.0001) (Fig. 3A and Table 2), respectively. As well, there was a *Condition* effect for stride frequency (p < 0.0168; F(1.000, 13.000) = 7.517) that was numerically lower at PRE by − 4.8 ± 6.6% (p = 0.0586) and at POST by − 4.9 ± 4.5% (p = 0.0109). In addition, there was a *Condition* effect for loading rate (p = 0.0237; F(1.000, 12.000) = 6.697) that was lower with poles. There was a *time* effect on contact time (p = 0.0008; F(1.000, 13.000) = 18.63) that was shorter at POST compared to PRE (Table 2).

Poling force at POST was lower (− 8.4 ± 8.2%, p = 0.0026) than at PRE (Fig. 3B and Table 2), as well as, the recovery phase was shorter at POST (− 5.7 ± 7.5%, p = 0.0217) compared to PRE.

Discussion

The main results of the present research are that (1) CoT_{vert} increases after a simulated trail running competition; (2) at POST, CoT_{vert} is lower when athletes use poles compared to when they do not use poles; (3) when athletes use poles the foot force is lower than when they do not use poles and (4) participants exerted less force with their upper limbs at the POST assessment.

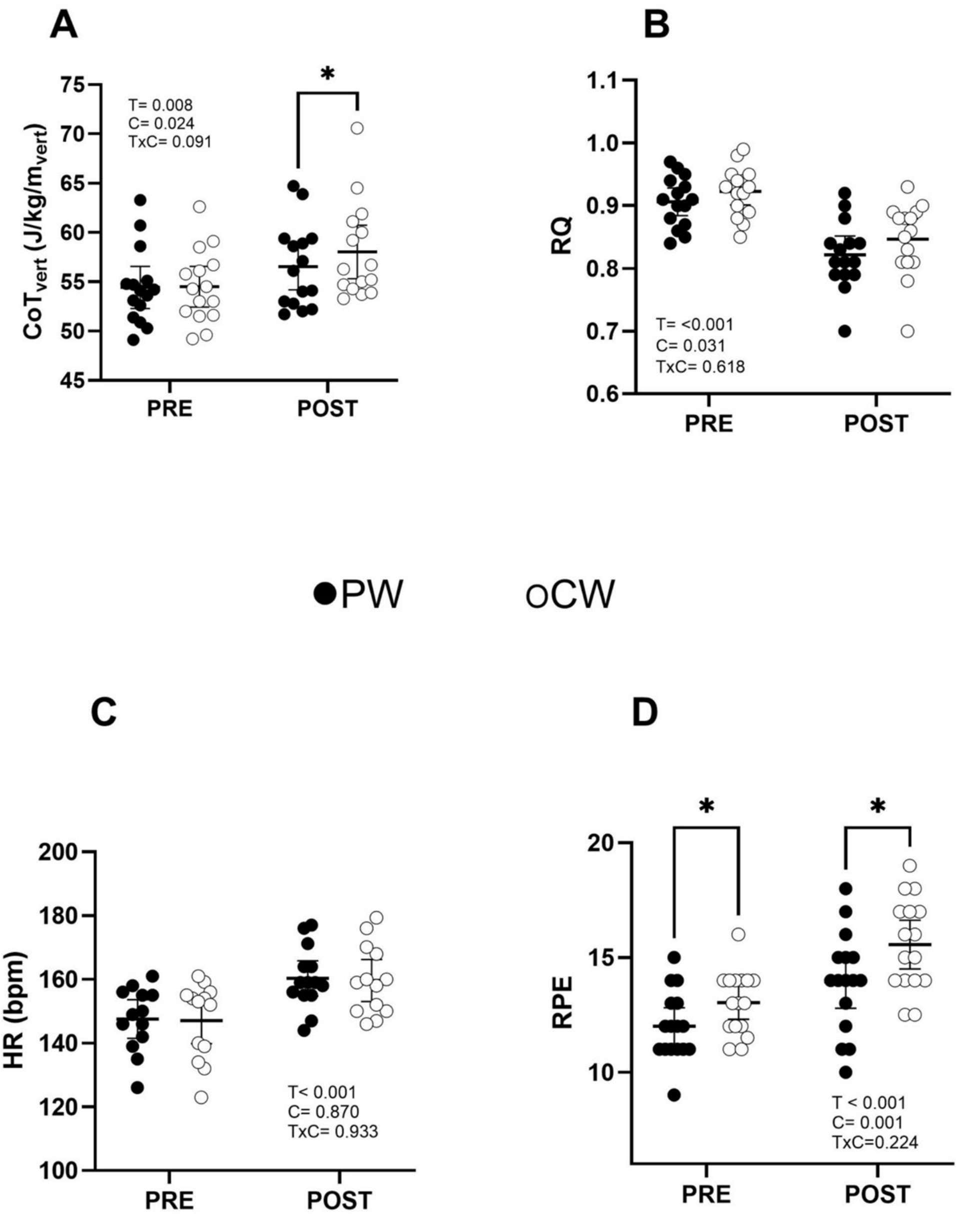

Fig. 2 Vertical cost of transport (CoT_{vert}, **A**), respiratory quotient (RQ, **B**), heart rate (HR, **C**) and rating of perceived exertion (RPE, **D**) before (PRE) and after (POST) the simulated trail running competition in participants walking with (PW) and without (CW) poles on the incline treadmill. The ANOVA results are reported for every panel (T = time, C = condition). * Post hoc comparison between PW and CW $p < 0.05$

As expected, CoT_{vert} was higher at POST compared to PRE. This finding aligns with previous studies demonstrating increased energy demand following trail running events of varying distances and elevation gains (Lazzer et al. 2014, 2015; Schena et al. 2014) although some authors have reported contrasting results (Vernillo et al. 2014, 2017; Sabater Pastor et al. 2021). It is worth noting that in these studies, CoT was measured without poles and participants were instructed to run. In contrast, our study focused on uphill walking. We specifically assessed the CoT during both pole walking and conventional walking, as our goal was to expand the understanding of CoT on uphill sections before and after a long trail running event, a context in which most athletes predominantly walk. Indeed, running with poles is uncommon on uphill sections. Furthermore, when speed exceeds the walk–run transition threshold the use of poles does not enhance performance (Giovanelli et al. 2022). However, the differences in study design (particularly the use of poles during PRE and POST tests) prevent a direct comparison between our findings and those of previous studies.

Cost of transport associated with pole use must be contextualized. Specifically, it has been shown that using poles during Nordic walking (i.e., on flat or slightly uphill terrain) increases the CoT, likely due to the greater muscular involvement not providing a proportional advantage in aiding forward progression (Saunders et al. 2008; Hansen and Smith 2009; Pellegrini et al. 2015). However, when the CoT is measured on a treadmill steeper than 20°, the CoT was

Table 2 Physiologic and biomechanical parameters before (PRE) and after (POST) the simulated trail running competition during walking without (CW) and with (PW) poles

	PRE		POST		T	C	TxC
	CW	PW	CW	PW			
CoT_{vert} (J/kg/m)	54.5 ± 3.7	54.4 ± 3.9	58.0 ± 4.9	56.5 ± 4.2	**0.008**	**0.024**	0.091
VE (L/min)	79.6 ± 10.3	79.0 ± 9.7	89.8 ± 13.2	85.9 ± 11.0	**0.000**	0.059	**0.005**
RQ	0.92 ± 0.04	0.91 ± 0.04	0.85 ± 0.06	0.82 ± 0.06	**0.000**	**0.031**	0.618
HR (bpm)	147.1 ± 12.0	147.5 ± 10.0	159.7 ± 10.9	160.3 ± 9.6	**0.000**	0.870	0.933
RPE	13.0 ± 1.4	12.0 ± 1.5	15.6 ± 2.0	13.9 ± 2.2	**0.000**	**0.001**	0.224
[BLa] (mmol/L)	2.4 ± 0.8	2.4 ± 1.1	2.4 ± 0.7	2.0 ± 0.7	0.152	0.139	0.125
FF (N)	362.3 ± 38.7	347.6 ± 31.1	350.0 ± 37.4	326.4 ± 46.5	0.070	**< 0.001**	0.9522
SF (stride/min)	52.2 ± 3.7	49.7 ± 4.2	54.3 ± 5.1	51.6 ± 5.2	0.053	**0.017**	0.969
fTcont (s)	0.71 ± 0.06	0.75 ± 0.08	0.68 ± 0.07	0.71 ± 0.07	**0.001**	0.300	0.176
peakLRF (N/s)	7997 ± 1559	7358 ± 1864	9079 ± 2235	8285 ± 2707	0.584	**0.024**	0.319
PF (N)		36.2 ± 8.2		33.0 ± 7.6	**0.003**	NA	NA
Poling frequency (cycles/min)		48.2 ± 4.2		50.1 ± 5.2	0.097	NA	NA
pTcont (s)		0.638 ± 0.077		0.631 ± 0.080	0.722	NA	NA
peakLRP (N/s)		854.5 ± 532.5		971.4 ± 577.3	0.099	NA	NA

In **bold** $p < 0.05$

CoT_{vert} vertical cost of transport; *VE* ventilation; *RQ* respiratory quotient; *HR* heart rate; *RPE* rating of perceived exertion; *[BLa]* blood lactate concentration; *FF* foot force; *SF* stride frequency; *fTcont* foot contact time; *peakLRF* maximal value for loading rate for foot; *PF* poling force; *pTcont* pole contact time; *peakLRP* maximal value for loading rate for poles; *T time* effect; *C condition* effect

lower when subjects used poles (Giovanelli et al. 2019). In this case, conversely to the flat terrain, the use of poles provides a significant advantage to the progression.

However, our study demonstrated that during both maximal and submaximal uphill tests on a mountain trail, the required metabolic power is not different between using or not the poles, but there was a force redistribution between upper and lower limbs (Giovanelli et al. 2023). This redistribution may facilitate workload distribution across a greater muscle mass during ascent, potentially mitigating fatigue development in the lower limbs.

As we hypothesized, CoT_{vert} was lower with poles at POST but not at PRE. This result agrees with a previous study in which we demonstrated that in non-fatigued conditions at inclines lower than 20° there is no differences between walking with poles or without (Giovanelli et al. 2019). Indeed, before the STRC the post hoc test did not reveal differences between the two conditions (to note that the incline of the treadmill was 18.6°). However, at POST, CoT_{vert} was lower when participants used poles. This result suggest that poles contribute to lower the CoT_{vert} in fatigued conditions. Although the force applied to the poles decreased after fatigue, this does not appear to have affected the force transmitted through the feet, as it did not change significantly in the post-fatigue condition. Therefore, we cannot determine whether the reduction in pole force contributed to the observed increase in CoT_{vert} following the STRC. It is important to note that previous research has demonstrated that the use of poles provides a performance advantage only when the speed is slower than the walk–run transition speed (Giovanelli et al. 2022). For this reason, in our study design, we selected a treadmill incline that required a belt speed slower than the walk–run transition speed to achieve the target vertical velocity (Brill and Kram 2021). Specifically, at the chosen incline, the energetically optimal transition speed has been calculated as 1.39 m/s (Brill and Kram 2021), which is significantly faster than the actual speed used during testing (0.92 ± 0.16 m/s).

An interesting observation is that respiratory quotient was lower when participants used poles. It is important to note that a lower RQ indicates a reduced reliance on carbohydrates (CHO) oxidation to meet energy demands. In prolonged endurance events, even a small reduction in CHO utilization per minute can accumulate significantly over several hours of exercise, potentially enhancing performance. However, this finding contrasts with expectations, as upper body muscles typically exhibit a lower capacity for fat oxidation and a greater reliance on CHO as an energy substrate even in athletes who regularly train also the upper limbs (e.g., cross country skiers) (Ortenblad et al. 2018; Helge 2010). Thus, one might anticipate that greater involvement of upper body muscles would increase CHO utilization. In addition, RPE was consistently lower when participants used poles. This aligns with previous studies reporting reduced RPE with the use of poles in various contexts (Howatson et al. 2011; Giovanelli et al. 2019; Saunders et al. 2008). In the present study, the lower RPE with poles may be attributed to two factors:

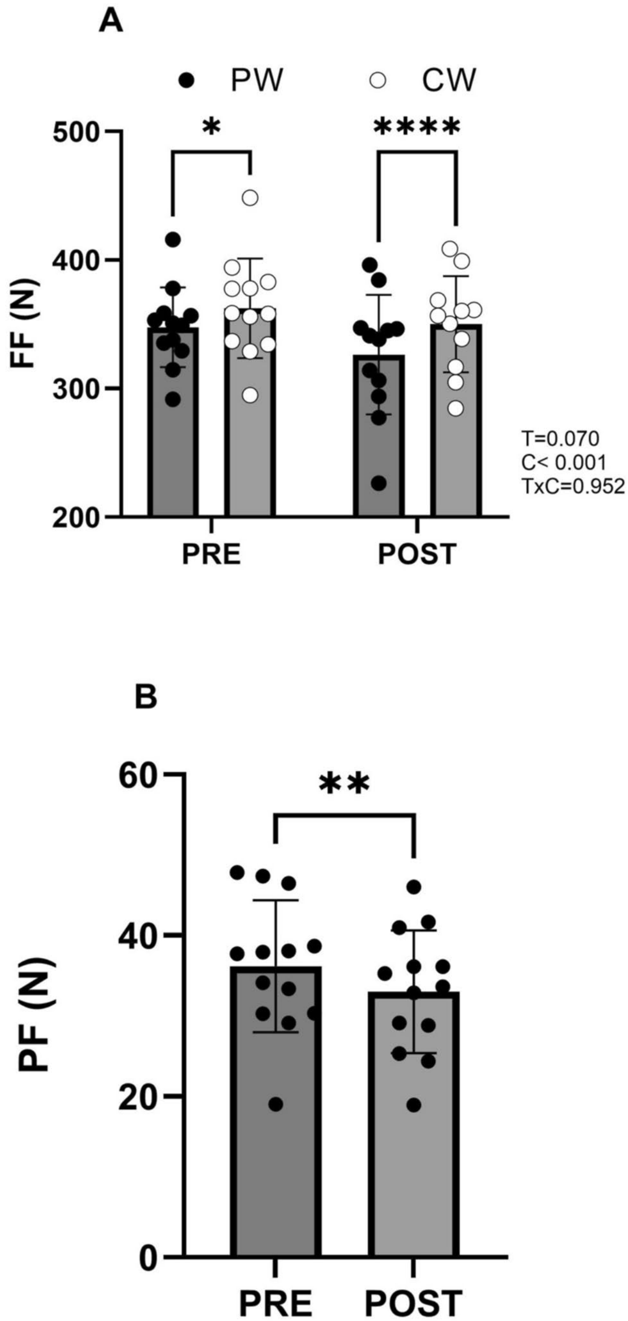

Fig. 3 Foot force (FF, **A**) registered before (PRE) and after (POST) the simulated trail running competition in participants walking with (PW) or without (CW) poles on the incline treadmill. Poling force (PF, **B**) registered before (PRE) and after (POST) the simulated trail running competition during the PW trial on the incline treadmill. ** < 0.01 The ANOVA results are reported (T = time, C = condition). Comparison between PW and CW *$p < 0.05$ **$p < 0.01$ ****$p < 0.0001$

(1) the redistribution of workload between upper and lower limbs, and (2) the reduced energy demand associated with pole use. Furthermore, considering that fatigue reduces the workload corresponding to the GET (Stevenson et al. 2022), and that PRE and POST tests were conducted at such a similar intensity, it is plausible that during the POST test, the conventional walking trial exceeded the GET for some participants, whereas the pole walking trial remained below this threshold. This suggests that the relative intensity of the two conditions may have fallen into different physiologic domains for some athletes, as partially supported by the similar HR values POST STRC but accompanied by different physiologic responses. However, a more targeted study design would be required to explore this aspect in greater detail. A brief consideration concerns heart rate response. As previously demonstrated, the use of poles during uphill locomotion does not significantly affect HR at maximal or submaximal intensity in non-fatigued subjects (Giovanelli et al. 2022, 2019). However, in the present study we observed elevated HR values following the STRC. This higher HR likely results from multiple factors associated with endurance exercise, including dehydration, reduced stroke volume and elevated body temperature (Coyle and Gonzalez-Alonso 2001).

As previously reported (Giovanelli et al. 2023; Daviaux et al. 2013) the use of poles reduces foot force. This phenomenon has been observed across various sports and conditions, as reviewed by others (Saller et al. 2023), as well as at different exercise intensities, both on a treadmill and on mountain path (Giovanelli et al. 2023). In the present study, foot force during CW was approximately 4% higher than during PW in both PRE and POST tests. These results are consistent with our previous work (Giovanelli et al. 2023), in which we reported similar differences in both treadmill and overground conditions. Contrary to our initial hypothesis, however, participants did not rely more on pole support (i.e., apply greater poling force) after completing the 31.2 km trail run, despite fatigue and likely EIMD in the lower limbs caused by the elevation loss during downhill sections (Millet et al. 2011; Saugy et al. 2013). Instead, poling force decreased after the STRC. One possible explanation is that the upper limbs, which have a higher proportion of fast-twitch, less-fatigue resistant muscle fibers even in trained athletes (Ortenblad et al. 2018), may have experienced fatigue due to the prolonged use of poles during uphill sections. Consequently, participants applied less force to the poles after the STRC. It is noteworthy that participants lost an average of 2.7 kg during the STRC. This weight loss likely explains the observed changes in average foot force, although not statistically significant, between PRE and POST fatigue condition during CW. In addition, this weight variation likely influenced foot force measurements during pole walking, contributing to the variation of POST values.

In addition, while it has been demonstrated that using poles during downhill sections reduces the EIMD (Howatson et al. 2011), athletes in our study reported not using poles during downhill, likely due to the high speed typically achieved in these segments. It is worth noting that in the study of Howatson et al. (2011), participants hiked rather than ran, resulting in significantly lower exercise intensity (~60–70 HRmax) compared to our study (~81% HRmax).

Other biomechanical parameters were minimally influenced by pole use. Stride frequency was lower with poles, as previously reported (Giovanelli et al. 2019). As well, loading rate was lower with poles, likely because of the lower weight supported by the lower limbs. However, the absence of a time effect suggests that pole use mitigates the fatigue-related changes in kinematic parameters previously reported (Vernillo et al. 2014). This, combined with the energy-saving benefits and reduced foot force required to maintain the same vertical speed, provides further support for encouraging athletes to use poles in long-lasting endurance events.

A limitation of our study design was the absence of maximal voluntary contraction force measurements for the upper and lower limbs before and after the STRC. Including such measurements, along with a STRC performed without poles, would have allowed for a more comprehensive comparison of the effects of pole use on muscle force and long-term performance. Another limitation of our study is that we measured only the gross CoT and not the net CoT. This decision was based on several considerations. First, measuring resting metabolic rate immediately before the test may prevent participants from achieving a fully relaxed state, as wearing the mask and equipment often elevates physiologic parameters beyond true resting levels, likely due to performance-related stress. Second, we cannot assume that the resting metabolic rate (to be subtracted from the gross metabolic rate) remains constant throughout the exercise. Finally, this approach ensures consistency with our prior studies (Giovanelli et al. 2016, 2019, 2022, 2023), which also used gross CoT measurements.

In conclusion, we demonstrated that using poles during uphill walking allows participants to save energy under fatigued conditions. From a practical perspective, pole utilization may mitigate the effects of fatigue during prolonged races, as evidenced by reductions in RPE, ventilation, RQ, and CoT_{vert}. Furthermore, it may help preserve muscular engagement during ascent, allowing athletes to exert greater force in subsequent sections. Previous studies showed that pole use increases vertical speed without additional metabolic demand. Our current findings provide scientific evidence supporting the strategic use of poles during prolonged endurance events. However, several aspects require further investigation, including: (1) pole utilization during downhill sections, (2) quantitative assessment of fatigue aspects, (3) direct measurement of EIMD, (4) controlled comparison of pole versus non-pole use on identical course, and (5) durability evaluation at specific intensities with and without poles.

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Author contributions All authors contributed to the study conception and design. NG, LM, MD collected the data. BP, LB analyzed the force-related data. NG, LM, and MD analyzed the metabolic data. NG and LM prepared the figures. The first draft of the manuscript was written by NG. All authors contributed to revising and improving subsequent versions of the manuscript. All authors read and approved the final manuscript.

Data availability The data that support the findings of this study are available from the corresponding author, NG, upon reasonable request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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