Energetic Cost of Running in Track and Treadmill

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Abstract: The metabolic power and cost of running per unit distance on a track have been estimated and compared with data collected indoor, in a laboratory on a treadmill. Oxygen uptake have been collected using a portable device, while speed was regulated by auditory feedback (metronome) and verified using GPS. Speed fluctuations remained within an acceptable range. Metabolic power increased linearly with speed, with a slope significantly lower on the track than on the treadmill ($p = 0.017$). However, statistical comparisons at the same speed did not yield significant differences between the two conditions. The average cost of transport was slightly, but not significantly, lower on the track (4.20 J/kg/m) than on the treadmill (4.35 J/kg/m), and it remained nearly independent of speed over a wide range. Nevertheless, in the lower and higher speed ranges on the track, the cost of transport tended to increase. A similar non-linear trend was observed in the cost of transport in relation to step frequency, with the minimum values falling within a range of 160 to 180 steps per minute. These preliminary results are encouraging and warrant further research to explore the differences between running on a treadmill and on a track.

1 INTRODUCTION

Motorized treadmills are widespread tools in research laboratories specialized in exercise physiology and biomechanics of locomotion. They are also widely used on a professional level in rehabilitation and sport, by runners, coaches and practitioners. One question that arises pertains to the reliability of information collected in the laboratory when it is applied to real outdoor conditions (Jones and Doust, 1996). Lindsay et al. (2014) demonstrated that quantifying gait parameters during treadmill running can yield different results compared to overground settings.

While it is not a novel topic, the energetic cost of human running is worthy of further investigation, especially under racing-like conditions, such as those found on an athletic track. The metabolic power and the metabolic cost of running per unit distance are determined by analyzing oxygen uptake in relation to speed. (Schmidt-Nielsen, 1972).

The speed control in track is a challenge that have been met in different ways: with a human guide (Jones and Doust, 1996; Tam et al., 2012), with a laser or light guide (Minetti et al., 2013; Pind et al., 2019), with an auditory feedback (Lagos et al., 2023). Minetti et al. (2013) demonstrated that smooth fluctuations of the running speed does not affect the metabolic cost, allowing for less strict control of speed.

The effect of air resistance, which is absent while running "in place" on a treadmill, have been

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addressed by Pugh (1970; 1971), that produced equations to estimate the extra-cost to win air resistance in track. Other researchers followed the suggestion of Jones and Doust (1996) of adding a 1% gradient to the treadmill trials, in order to compensate the lack of air resistance on treadmill, but with controversial results (Mooses et al., 2015; Pind et al., 2019).

Initial comparisons between treadmill and track results were conducted using Douglas bags for gas analysis (Pugh, 1970; Basset et al., 1985; Jones and Doust, 1996). However, the use of these cumbersome tools adversely affected running performance and yielded questionable results (Mooses et al., 2015). More recently, with the availability of portable metabolic devices, other research projects have tackled this question by analyzing the metabolic cost of running outdoors (Tam et al., 2012), or by comparing the cost between treadmill and track settings (Mooses et al., 2015; Pind et al., 2019). These recent studies have indicated better running economy (lower metabolic cost) on a track compared to treadmill conditions. It is important to note that both Mooses et al. (2015) and Pind et al. (2019) involved endurance runners as participants. The findings of Tam et al. (2012) were consistent, and they were also obtained through an analysis of elite marathon runners.

The objective of this ongoing project was to analyse the energetic cost of running on a track using a portable metabolic device, GPS, and auditory feedback for speed control. The study involved a diverse sample of athletes from various sports disciplines and aimed to compare the results with data collected indoors on a treadmill.

2 METHODS

A total of 56 healthy men participate in this research, they were measured and weighed in the lab, prior to the trials (Age 28 ± 10 years; Weight 74.9 ± 11.2 kg; Height 177 ± 7 cm). All participant were runners with weekly volume of 5 to 25 km, with at least 1 year of continuous practice.

2.1 Data Collection

Part of the treadmill metabolic data used in this research have been collected by the authors during a period from 2016 and 2022, and published in previous works and/or available in public repositories (Lagos et al., 2022; Lagos et al., 2023; Pequera et al., 2020; Pequera et al., 2023). New treadmill (3 subjects) and track (22 subjects) metabolic data have been collected in 2023 at the Biomechanics and Movement Analysis Research Laboratory (LIBiAM) of the Universidad de la República in Paysandú, (Uruguay) at a controlled temperature of 22°C, and at the athletic track in the Polideportivo Paysandú (certified by the International Association of Athletics Federations), at an average temperature of 22 ± 2 °C with almost no wind. All procedures were in accordance with the latest version of the Declaration of Helsinki (2013). The study protocol was approved by the Ethics Committee of the CENUR Litoral Norte—Universidad de la República (Exp. #311170-000921-19).

Metabolic data were collected breath by breath by a wearable metabolic system (K5, Cosmed, Italy). Reference resting values of each participant were assessed by a first record of 5 minutes in a quiet orthostatic position. Trials, performed according to the protocol described below, lasted 5 minutes each, but only the last minute of each trial, when a steady state oxygen flow was reached, was considered for energetic analyses.

Cosmed K5 includes an integrated GPS (position accuracy within 2.5 m and speed accuracy within 0.1 m/s) (De Blois et al., 2021).

2.2 Treadmill Protocol

After a session of familiarization with the treadmill, they realised between three and six running trials on a treadmill (T2100, General Electric, USA) at controlled constant speeds, in a range between 1.67 and 3.61 m/s. Further details in Pequera et al. (2023).

2.3 Track Protocol

The preparation was performed directly in the track (200 m from the lab location). Data collection was performed during mild uruguayan autumn days, with comfortable temperatures and wind almost absent. A 10 m speed trap was positioned along the straight stretch, were the performance was recorded with a portable device mounted on a tripod for afterwords control.

In the first trial, participants were asked to perform a 5-minutes run, maintaining a constant pace at their comfortable running speed, in the lane 6 of the track. The step frequency maintained during the trial was measured thrice, and the average value was recorded as the preferred step frequency (*Psf*, beats per minute) and was used to compute the rules for the following trials.

During the second and third trials, participants were asked to wear a headset connected to a smartphone. Auditive feedbacks of a metronome performing a beat frequency were provided (Metronome.com, click sound, ¼ time), and runners were asked to adapt their step frequency to the sound (one heel strike every click, minding that two steps corresponds to one stride). During the second trials the beat frequency was 15% slower than the *Psf*, while during the third trial it was 15% faster than the *Psf*. A resting period of 3-5 minutes was observed between two trials.

2.4 Data Analysis

The net oxygen uptake was computed by subtracting the average resting value from the average oxygen flow rate ($\dot{V}O_2$) measured during the last minute of each trial. Respiratory quotient (RQ), the ratio between CO_2 and O_2 flow rates, was also averaged during the last minute of the trial, and used to convert mlO_2 to Joules (di Prampero 2015). The net metabolic power (MetP; W/kg) so obtained was divided by the forward speed (m/s) in order to achieve the running economy, or cost of transport (CoT; J/kg/m), the metabolic energy needed to move one unit mass one unit distance (Schmidt Nielsen, 1972).

When running outdoors we need to consider an extra-cost, which would account for the energy required to overcome the air resistance, absent during indoor treadmill exercises (Jones and Doust, 1996). The resulted values of oxygen uptake in track were corrected using the equation (1) provided by Pugh (1971), assuming a wind speed equal to the forward speed (calm or absent wind):

$$\Delta\dot{V}O_2 = 0.00354 \cdot A_e \cdot v^3 \quad (1)$$

where $\Delta\dot{V}O_2$ is the fraction of $\dot{V}O_2$ necessary to win the air resistance, in L/min; A_e is the body surface projected area, which was assumed constant at the value of 0.436 m^2 (Pugh, 1970); and v is the wind speed in m/s.

Videos collected during the track protocol were analysed to check the forward speed and the observed step frequency (*Osf*).

ANOVA and Student *t*-test, or the equivalent non-parametric Kruskall-Wallis and Mann-Whitney U-test were applied, depending on the results of normality test. Alpha was set to 0.05, effect size was expressed as Cohen's d. Linear or quadratic regression was applied to fit the data. Magnitude of association (Pearson's r) and coefficient of determination (r^2) were showed.

3 RESULTS AND DISCUSSION

3.1 Speed in Track

GPS speed was compared with the speed obtained by video analyses, with a difference < 2%, within the speed accuracy declared by Cosmed.

The participants were able to maintain an almost constant speed during the track trials, at least after a first part of "speed adaptation", which occurred during the first minute of each trial. The 5 minutes duration of each exercise protects our data from possible negative effects of the first adaptation stretch, as the steady-state of oxygen flow rate during running is attained within 2 minutes at constant speed (Carter et al., 2000).

The energetic cost of running is not affected by cycles of acceleration/deceleration (Minetti et al., 2013). However, our purpose was to compare track and treadmill under similar conditions. The speed in track was recorded by GPS simultaneously with physiological parameters, therefore breath-by-breath and not at a constant rate. We computed the standard deviation (SD) of the speed along the period used for the energetic cost calculation. We obtained an average SD of 0.13 m/s during the first trial, at comfortable speed, and an average SD of 0.11 m/s during the trials supported by auditory feedback, which helped to maintain a constant pace (Lagos et al., 2023).

3.2 Metabolic Power

In both conditions the MetP linearly increased with speed (Figure 1). Both regressions lines were statistically significants ($p < 0.001$). On the treadmill the slope resulted 4.56, $r = 0.87$, $r^2 = 0.75$. On the track the slope resulted 3.65, $r = 0.85$, $r^2 = 0.72$. Both, magnitude of association and coefficient of determination indicate a strong relationship (Thomas and Nelson, 2001). The slope difference was statistically significant ($F = 5.77$; $p = 0.017$).

The trend of the treadmill results is in agreement with previous works, where the slope of the MetP vs. speed relationship was > 4 (Tam et al., 2012; Kipp et al., 2018; Pind et al., 2019), while in an analysis of half-marathon and marathon runners the MetP increased with a slope of about 3 with respect to speed (Di Prampero et al., 1986). The slope of the regression in track was slightly less than that obtained in previous works with a similar protocol (Tam et al., 2012; Pind et al., 2019).

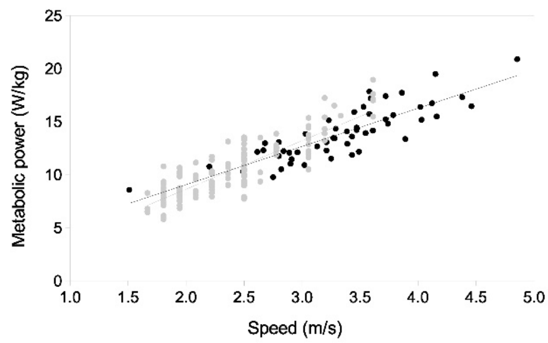

Figure 1: Metabolic power vs. speed. Grey circles: treadmill experiments; Black circles: track experiments. Regression lines are displayed accordingly.

3.3 Cost of Transport

The CoT was obtained by dividing the MetP for the forward speed. Therefore, assuming that the intercept of MetP at rest should be nearly zero, we would expect an almost constant (speed independent) CoT in a range from 3.5 to 4.5 J/kg/m. The overall mean CoT in treadmill (4.35 ± 0.55) was not significantly different from the overall mean CoT in track (4.20 ± 0.45): U Mann Whitney = 3325, p = 0.09, d = -0.16. When the number of observations allowed to compare treadmill and track at the same speed, no significant difference were found in both CoT and MetP (Table 1). Differently from our results, Mooses et al. (2015) and Pind et al. (2019) found a significantly lower CoT overground than on a treadmill. However, they analysed high level endurance runners on a narrower range of speeds.

Table 1: Results of a *t*-test between treadmill and track results at different speeds. Speeds in m/s; df = degrees of freedom; d = Cohen's d (effect size).

Forward speed	**CoT *t*-test**	**MetP *t*-test**
2.64 (df = 5)	p = 0.173; d =1.22	p = 0.162; d =1.25
2.78 (df = 9)	p = 0.100; d =-1.12	p = 0.141; d=-0.98
3.06 (df = 20)	p = 0.998; d =-0.01	p = 0.997; d =0.01
3.19 (df = 7)	p = 0.162; d =-1.05	p = 0.197; d=-0.96
3.61 (df = 8)	p = 0.358; d =-0.62	p = 0.308; d=-0.69

The speed-independent behaviour of the cost of transport (CoT) has been documented in various studies (Kram and Taylor, 1990; Minetti et al., 2013; Arellano and Kram, 2014; Pavei et al., 2015; Pequera et al., 2023). However, there is some evidence suggesting that the cost of running may not be entirely independent of running speed, particularly among elite runners and at speeds beyond the average range (Batliner et al., 2018). Our results regarding CoT vs. speed are summarized in Figure 2. On the treadmill, the coefficient of determination for the linear model was $r^2 = 0.11$. On the track, where a wider range of speeds was achieved, a non-linear pattern appears to emerge, with higher CoT values observed at very low or very high forward speeds (Degree 2 polynomial: $r^2 = 0.24$).

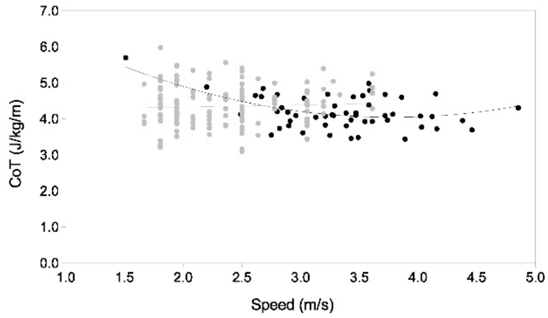

Figure 2: Cost of transport vs. speed. Grey circles: treadmill experiments; Black circles: track experiments. Best fit curves are displayed accordingly.

3.4 CoT and Step Frequency

In figure 3 the CoT was plotted versus the step frequency (Spm: steps per minute). Both treadmill and track distributions displayed a quadratic fit line: treadmill $r^2 = 0.14$; track $r^2 = 0.34$. The minimum of both trend lines corresponds to a range of step frequencies between 160 and 180 Spm.

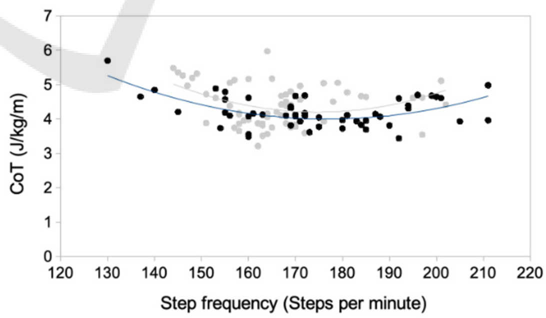

Figure 3: Cost of transport vs. step frequency. Grey circles: treadmill experiments; Black circles: track experiments. Best fit curves are displayed accordingly.

These results align with the preferred and optimal step frequencies identified by Snyder and Farley (2011) and Lieberman et al. (2015), which were approximately 170 steps per minute (Spm) in both cases. In running, variations in speed are primarily attributed to changes in stride length rather than stride (or step) frequency (Cavanagh and Kram, 1989; Lieberman et al., 2015). It is important to note that the cost of transport (CoT) is considered one of the determinants of the optimal step frequency, although mechanical variables such as peak forces and torques also play a role.

4 CONCLUSIONS

Modern equipment and technology enable us to measure the energetic cost of locomotion using experimental setups that closely mimic racing-like conditions. Although our research is ongoing and not yet finalized, our preliminary results have revealed significant differences in the rate of metabolic power increase with respect to speed between running on a track and running on a treadmill. Additionally, we observed a slightly better running economy on the track compared to the treadmill, although the cost of transport (CoT) did not exhibit a significant difference. Furthermore, our findings provided insights into an optimal range of step frequencies that appear to minimize CoT.

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