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Influence of surface condition and prolonged running on impact accelerations

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ABSTRACT

Running can be performed on different types of surfaces with distinct characteristics. These differences between the running surfaces may affect impact accelerations during prolonged running. The aim of this study was to compare the effect of the type of running surface (motorised treadmill (MT), curved non-motorised treadmill (cNMT), and overground (OVG)) and prolonged running in impact accelerations, spatiotemporal parameters and perceptual variables. In the current study, twenty-one recreational runners completed three randomised crossover prolonged running test on these surfaces consisting of a 30-minute run at 80% of the individual maximal aerobic speed. A two-way repeated-measure analysis of variance, with the level of significance set at $p < 0.05$, showed a reduction in impact accelerations, such as tibia peak acceleration, when running on cNMT vs MT ($p = 0.001$, ES = 4.2) or OVG ($p = 0.004$, ES = 2.9). Running on cNMT produced an increase in stride frequency ($p = 0.023$, ES = 0.9) and higher rating of perceived effort ($p < 0.001$, ES = 8.9) and heart rate ($p = 0.001$, ES = 2.9) compared to OVG, with no differences between treadmills. These findings suggest that impact accelerations, spatiotemporal parameters, rating of perceived exertion and heart rate are different between the surfaces analysed, what should be taken into consideration when running on these surfaces.

Introduction

Running has become an important global phenomenon and the sport equipment market is constantly evolving and growing trying to satisfy athletes' demands, making motorised treadmills (MT) one of the most relevant tools for sport purposes, research, exercise testing, and rehabilitation (Milner et al., 2020). Treadmills present some methodological advantages over asphalt, grass or track, i.e., easier instrumentation, better control of the environment (temperature, humidity), the possibility of maintaining a certain speed and slope requiring less space with high test replicability (García-Pérez et al., 2014).

Although some studies suggest that MT running can be a representative expression of overground running (OVG) (Riley et al., 2008; Schache et al., 2001), other studies suggest that different running surfaces (e.g., treadmill, asphalt, indoor track or outdoor sidewalk) may lead to certain biomechanical variations, such as stride frequency (Hunter & Smith, 2007), joint kinematics (Schache et al., 2001; Wank et al., 1998), impact accelerations (Milner et al., 2020), contact time and plantar pressures

(García-Pérez et al., 2013) or energy cost (Pind et al., 2019).

According to Van Hooren et al. (2019), the differences on these surfaces could be due to stiffness, comfort and insufficient treadmill familiarisation, treadmill power, air resistance difference or the altered speed perception. Another study (Frishberg, 1983) assures that these changes exist because the moving treadmill belt requires less propul- sion, reducing the energy demands of the runner by bringing the supporting leg back under the body during the support phase of running rather than the body moving over the supporting leg while running overground.

New treadmill designs, such as curved non-motorised treadmills (cNMT), allow runners to self-select the speed by driving the belt, running on a more ecological environment (Schoenmakers & Reed, 2020). The cNMT has been previously investigated for biomechanical variables, such as impact accelerations (Encarnación-Martínez et al., 2021), spatiotemporal kinematics (Bruseghini et al., 2019; Hatchett et al., 2018), percep- tual demands (Schoenmakers & Reed, 2020) and physiological parameters such as blood lactate, heart rate (HR), maximal oxygen consumption (VO2max) and running economy (Edwards et al., 2017; Smoliga et al., 2015). Previous studies have shown a reduction in impact accelerations (Encarnación-Martínez et al., 2021; Milner et al., 2020), higher perceptual and physiological variables (i.e., rating of perceived exertion, heart rate or VO2max) (Bruseghini et al., 2019; Encarnación-Martínez et al., 2021), but no differences in spatiotemporal parameters (i.e., stride length and frequency) (Encarnación-Martínez et al., 2021; Seneli et al., 2011) while running on cNMT vs MT. Impact accelerations have also been studied during OVG vs MT (Aubol et al., 2020; García-Pérez et al., 2014; Milner et al., 2020), concrete vs grass (Waite et al., 2020), woodchip trail vs synthetic track vs concrete (Boey et al., 2017).

Impact accelerations are related to an increase in the risk of injury (Pérez-Soriano et al., 2018). During the foot contact with the ground while running, the rapid deceleration is transmitted from the tibia to the head throughout the skeletal system (Derrick, 2004; Hines & Mercer, 2004). The energy of this impact acceleration at heel strike is absorbed not only by muscles, bones and other structural tissues, but also by running shoes and running surface (Boey et al., 2017; Encarnación-Martínez et al., 2021). Approximately, 600 impacts per kilometre occur while running, which results in more than 600,000 impacts per year in training sessions of around 20 km/week (Derrick et al., 2002). Accelerometer-based analysis systems have been used routinely to continuously assess acceleration peaks during activities such as running and human gait, demonstrat- ing excellent validity and reliability (Van den Berghe et al., 2019).

During prolonged running, the cyclical and repetitive nature of running entails great demands on the musculoskeletal system, since it has to absorb 1.2 to 4 times the runner's body weight (Lieberman et al., 2010). Therefore, prolonged running fatigues reduces the ability of the musculoskeletal system to absorb impact accelerations as a result of the accumulated exposure to them, increasing the risk of injury (García-Pérez et al., 2014; Mercer et al., 2003). Interestingly, around 42.7% of runners around the world get injured each year, most of them due to overuse (Francis et al., 2019; van der Worp et al., 2015), finding men, particularly younger men (<40 years), to have an increased risk of running- related injuries than women (van der Worp et al., 2015).

Two of the most important factors affecting impact accelerations are running surface and prolonged running. For example, a reduction in impact accelerations while running on MT in comparison with OVG has been observed (García-Pérez et al., 2014; Milner et al., 2020). Different studies have suggested an increment of fatigue while running on MT compared to OVG (Pind et al., 2019) and higher ratings of perceived effort (RPE) during running at different speeds on cNMT vs MT (Encarnación-Martínez et al., 2021). Also, an increase in impact accelerations caused by fatigue has been observed after 30 minutes above the anaerobic threshold (Derrick et al., 2002; Mizrahi et al., 2000), what has been shown to be a sufficient time to induce general fatigue (Verbitsky et al., 1998). Therefore, the purpose of the current study was to compare impact accelerations between treadmill conditions (MT and cNMT) and OVG during a prolonged run. Based on the previously described factors that could influence tibia and head accelerations, the authors hypothesised that runners would experience lower impact accelerations during the cNMT running compared to MT and OVG. Second, the authors hypothesised that impact accelerations would increase as runners progressed through the test, due to prolonged running-related changes.

Methods

Experimental approach to the problem

A randomised crossover study with repeated measures design was carried out in order to analyse the differences between MT, cNMT and OVG during a prolonged run. Participants ran with their own shoes in all testing conditions to reduce any biomecha- nical variability (Jimenez-Perez et al., 2021; Lucas-Cuevas et al., 2018). The tests were separated by 1 week and were carried out in three different days at the same time of the day (±1 h).

Subjects

Twenty-one recreational runners: 17 males and 4 females (age 36 ± 9 years, height 1.76 ± 0.08 m, body mass 69 ± 10 kg, body mass index 22 ± 2 kg/m2, training frequency 4 ± 1 sessions/week, running load 41 ± 15 km/week) agreed to participate in the study and gave written informed consent. Inclusion criteria included to be between 18 and 50 years old, be physically active (considered as people who performed at least two trainings per week during the last year), no history of lower limb injuries within the last 6 months, a training volume of at least 20 km per week. Exclusion criteria included surgery, injury or illness within the previous 6 months, overweight or obesity (BMI >24.9 kg/m2), suffering of heart failure, musculoskeletal or neurological disorders affect-

ing normal locomotion and to be taking medication that interferes with stability during running. Participants usually ran OVG and were used to perform some trainings on MT; however, they had no previous experience on cNMT. Based on a general linear model (GLM) of two-way Repeated Measures design, a total sample size of 18 partici- pants was needed to detect significant differences associated with a minimum

detectable effect size (large) f = 0.50 (α = 0.05, β = 0.05, power = 0.9521) for impact accelerations. The study procedures complied with the Declaration of Helsinki and were approved by the University ethics committee (registry number: 1568868).

Procedure

Firstly, participants performed a submaximal test to determine the individual maximum aerobic speed (MAS) 48 hours before testing (Berthon et al., 1997). This test consisted the participants to cover the maximum distance running on a 400 m-track during 5 minutes at a constant speed (Berthon et al., 1997; Chamoux et al., 1996). Subsequently, participants carried out three running test on different surfaces: MT (h/p/cosmos pulsar® 3p, h/p/cosmos sports & medical gmbh. Nußdorf, Germany) with 1% incline to replicate the energy cost of outdoor running (Jones & Doust, 1996), cNMT (Bodytone ZRO-T, Bodytone International Sport S.L., Molina del Segura, Spain) and overground (300 m asphalt circuit). Similarly, on each surface, participants warmed-up for 8 min, which also served as familiarisation time (Arnold et al., 2019). Then, participants performed a 30-min test at 80% of the individual MAS. A completely randomised crossover design protocol throughout R Studio (version 5211.4.1103) was used for the surface order selection.

Impact accelerations, spatiotemporal parameters, RPE and HR were collected during minute 1, 5, 10, 15, 20, 25 and 30 of the test, hereafter referred to as T1, T5, T10, T15, T20, T25, and T30, respectively, based on previous investigations who also followed the protocol used in the current study in order to analyse the effect of fatigue (Izquierdo-Renau et al., 2021; Lucas-Cuevas et al., 2015). A total of 5.880 strides on each surface were analysed in the study.

Data collection

Acceleration and spatiotemporal parameters were registered at 120 Hz by two lightweight triaxial wireless accelerometers (XSENS DOT, XSENS, Enschede, Netherlands; total mass: g; dimensions: 36 _ 30 _ 11 mm, range ±16 g) (Cudejko et al., 2022). The accelerometers were placed on the forehead and the anteromedial distal portion of the tibia of the dominant leg, which was determined based on Van Melick et al. (2017). They were firmly attached to the skin with double-sided adhesive tape and secured by elastic neoprene belts, adjusting the pressure up to the participants' comfort limit (Encarnación-Martínez et al., 2018; Lucas-Cuevas et al., 2017). The vertical axis of the accelerometer was aligned to be parallel to the vertical axis of the tibia, since the location of the tibia accelerometer does influence the acceleration signal (Lucas-Cuevas et al., 2017).

Acceleration data was analysed using Matlab (MathWorks, MA, USA). The acceleration signal was filtered (Butterworth, second-order, low-pass, cut-off frequency = 50 Hz) and stride frequency (time between consecutive leg impact peaks, with units of strides per second (Hz)) and stride length (calculated by dividing the speed ($m·s^{-1}$) by stride frequency (Hz)) were calculated as spatiotemporal parameters (Mercer et al., 2002; Milgrom et al., 2003). As impact accelerations, tibia and head acceleration rate (slope from ground contact to peak accelera- tion), tibia and head peak acceleration (maximum value of the acceleration signal), tibia and head acceleration magnitude (difference between the positive and the negative acceleration peak) and shock attenuation (reduction in impact acceleration from the tibia to the head) were calculated from the acceleration signal (Encarnación-Martínez et al., 2021). A 6–20 Borg (1982) and portable HR belt (Polar V800, Polar Electro, Kempele, Finland) were used to register RPE and HR, respectively.

Statistical analysis

Statistical analysis was carried out using SPSS.26 statistics software package (SPSS Inc., Chicago, IL, USA). The data normality and homoscedasticity were verified using the Shapiro—Wilk test and Levene test, respectively. A general linear model of two-way repeated-measures design was performed for the 30-min test. Running surface (cNMT, MT and OVG) and prolonged running (T1, T5, T10, T15, T20, T25, and T30) were considered as within-subject factors. Post hoc comparisons were performed applying the Bonferroni correction to identify the location of specific differences. The level of significance was set at $p < 0.05$. For significant pair differences, effect size (ES) was assessed using Cohen’s d (0.2, small; 0.5, moderate; 0.8, large) (Cohen, 1992).

Results

Data analysis was carried out as homogeneous sample since no statistically significant differences ($p > 0.05$) were found in impact acceleration variables, spatiotemporal para- meters, RPE or HR between men and women.

Effects of running surface

Two way repeated measures ANOVA showed significant differences ($p < 0.05$) between running surfaces. Specifically, running on cNMT resulted in higher values than MT running in head rate acceleration ($p = 0.005$, ES = 2.6), head and tibia peak acceleration ($p < 0.001$, ES = 3.3; $p = 0.001$, ES = 4.2 respectively), head and tibia acceleration magni- tude ($p < 0.001$, ES = 3.6; $p < 0.001$, ES = 4.5 respectively) and attenuation ($p = 0.011$, ES = 2.5); whereas values were statistically higher on OVG surface compared to MT in head rate acceleration ($p = 0.010$, ES = 3.2), tibia peak acceleration ($p = 0.004$, ES = 2.9), tibia acceleration magnitude ($p < 0.001$, ES = 3.5) and attenuation ($p < 0.001$, ES = 4.7). Lastly, running on cNMT resulted in lower values than OVG running in head rate acceleration ($p < 0.001$, ES = 5.6), in head and tibia peak acceleration ($p = 0.021$, ES = 2.5, $p < 0.001$, ES = 6.8 respectively), in head and tibia acceleration magnitude ($p = 0.003$, ES = 2.9; $p < 0.001$, ES = 7.8 respectively) and in attenuation ($p = 0.011$, ES = 4.7) (Table 1).

In terms of spatiotemporal parameters, running on cNMT showed lower stride lengths compared to OVG ($p = 0.024$, ES = 0.9), and higher stride frequencies on MT vs OVG ($p = 0.023$, ES = 0.9) were observed (Figure 1). Furthermore, higher values were found when running on cNMT compared to OVG in terms of RPE and HR (RPE: $p < 0.001$, ES = 8.9; HR: $p = 0.001$, ES = 2.9), and higher values running on MT vs OVG (RPE: $p < 0.001$, ES = 8.6; HR: $p = 0.010$, ES = 2.0). In summary, the RPE and HR values were lower when running on OVG compared to the cNMT and MT treadmills, however no differences between treadmills (cNMT vs MT) were found (Figure 2).

Interaction's effect between surface and prolonged running

Prolonged running led to a significant impact acceleration reduction ($p < 0.05$) between the early vs final stage of the test. Specifically, these differences were present for head peak acceleration on MT at T5 vs T20 (p = 0.049, ES = 1.1) and on cNMT at T5 vs T15 (p = 0.036, ES = 0.9), T5 vs T20 (p = 0.042, ES = 1.3). For head acceleration magnitude, the differences were found on cNMT at T1 vs T20 (p = 0.047, ES = 1.4), T5 vs T15 (p = 0.015, ES = 0.9), T5 vs T20 (p = 0.023, ES = 1.4) (Table 1). However, prolonged running was not found to cause any significant difference ($p > 0.05$) in stride length, head/tibia rate, tibia peak, tibia magnitude or attenuation.

An interaction between surface and prolonged running was found in terms of stride frequency, where significant differences between the early vs final stage of the test were found on cNMT. Specifically, stride frequency decreased during the test, with significant differences between T1 vs T10 (p = 0.007, ES = 1.0), T1 vs T15 (p = 0.009, ES = 1.1), T1 vs T20 (p = 0.005, ES = 1.3), T1 vs T25 ($p < 0.001$, ES = 1.6), T5 vs T25 (p = 0.010, ES = 1.1), T5 vs T30 (p = 0.020, ES = 0.9), T10 vs T25 (p = 0.047, ES = 0.6); while during OVG running stride frequency increased during T10 vs T30 (p = 0.036, ES = 0.7).

RPE and HR increased significantly ($p < 0.05$) during the run, finding differences between the early vs final stage of the test (Figure 2).

Discussion and implication

The main objective of the present study was to analyse the influence of different running surfaces during a prolonged run in impact accelerations, spatiotemporal and perceptual parameters. To date, no studies have analysed head and tibia accelerations during a prolonged running protocol on cNMT in comparison with MT and OVG. Based on the findings, running on cNMT reduces impact accelerations and stride length while runners experience higher RPE and HR compared to OVG and MT. Also, significant differences were found between the early vs final stage of the test in all of the three surfaces, where a decrease in head peak, head magnitude and stride frequency was observed, while RPE and HR increased during the test.

Running on a cNMT produced lower impact accelerations compared to MT and OVG, where the highest impacts were observed on OVG surface. As previous studies have shown, surface stiffness could influence impact accelerations (Dixon et al., 2000) while running: MT vs OVG (Aubol et al., 2020; García-Pérez et al., 2014; Milner et al., 2020), concrete vs grass (Waite et al., 2020), woodchip trail vs concrete vs synthetic running track (Boey et al., 2017). However, other studies (Fu et al., 2015) did not find any differences in tibia impact across a wide range of surfaces, such as EVA (Ethylene-Vinyl Acetate) treadmill, MT, synthetic track, concrete or natural grass. In line with the results of our study, some investigations observed a reduction in impact accelerations on cNMT in comparison with MT (Encarnación-Martínez et al., 2021) and OVG (Montgomery et al., 2016), finding several factors that could

Table 1. Parameters (mean and standard deviation) based on surface and moment of the test.

Parameter	Surface	T1	T5	T10	T15	T20	T25	T30	*p* value (between surfaces)
Head rate (g/ms)	MT	32.12 (14.21)	30.5 (14.5)	33.43 (16.32)	33.62 (16.32)	34.2 (15.83)	34.68 (14.6)	32.47 (12.32)	$p < 0.001$
	cNMT	33.06 (12.76)	33.57 (13.53)	34.87 (15.29)	34.58 (13.86)	34.21 (13.62)	34.89 (14.78)	33.99 (16.87)	
	OVG	29.48 (13.28)	30.39 (13.51)	30.2 (14.98)	31.7 (15.53)	31.94 (16.34)	33.81 (16.03)	33.1 (16.83)	
Tibial rate (g/ms)	MT	163.5 (110.35)	159.36 (116.32)	150.54 (117.38)	152.53 (119.11)	159.88 (93.48)	185.99 (158.11)	184.66 (146.7)	N.S.
	cNMT	195.86 (153)	201.43 (158.86)	217.22 (148.75)	228.97 (168.38)	215.66 (135.26)	212.85 (147.48)	219.18 (145.33)	
	OVG	216.66 (158.25)	206.56 (179.84)	216.14 (172.94)	218.72 (176.88)	226.77 (209.68)	207.42 (169.97)	228.01 (208.75)	
Head peak (g)	MT	2.69 (0.29)	2.72 (0.32)	2.67 (0.29)	2.66 (0.32)	2.64 (0.33)^{b}	2.65 (0.29)	2.64 (0.29)	$p = 0.009$
	cNMT	2.48 (0.31)	2.47 (0.31)	2.44 (0.29)	2.43 (0.27)^{b}	2.4 (0.30)^{b}	2.41 (0.29)	2.45 (0.33)	
	OVG	2.77 (0.48)	2.76 (0.52)	2.75 (0.51)	2.71 (0.51)	2.71 (0.55)	2.66 (0.55)	2.65 (0.58)	
Tibial peak (g)	MT	7.41 (1.65)	7.6 (1.74)	7.71 (1.76)	7.63 (1.66)	7.58 (1.52)	7.6 (1.78)	7.62 (1.89)	$p < 0.001$
	cNMT	5.78 (1.76)	5.87 (1.70)	5.79 (1.67)	5.96 (1.70)	5.9 (1.63)	5.8 (1.46)	6.09 (1.68)	
	OVG	8.41 (1.69)	8.65 (1.89)	8.78 (1.95)	8.84 (1.89)	8.9 (2.24)	8.86 (2.24)	8.96 (2.23)	
Head magnitude (g)	MT	2.99 (0.42)	3.02 (0.44)	2.96 (0.41)	2.96 (0.42)	2.93 (0.43)	2.92 (0.39)	2.92 (0.4)	$p = 0.001$
	cNMT	2.66 (0.44)	2.66 (0.44)	2.6 (0.41)	2.59 (0.39)^{b}	2.54 (0.4)^{a,b}	2.56 (0.4)	2.62 (0.44)	
	OVG	3.05 (0.58)	3.05 (0.62)	3.03 (0.60)	2.98 (0.62)	2.99 (0.67)	2.92 (0.67)	2.93 (0.68)	
Tibial magnitude (g)	MT	8.89 (2.24)	9.24 (2.38)	9.4 (2.52)	9.28 (2.44)	9.13 (2.22)	9.26 (2.65)	9.28 (2.79)	$p < 0.001$
	cNMT	6.64 (2.07)	6.75 (2.07)	6.62 (2.15)	6.81 (2.17)	6.64 (2.00)	6.6 (2.01)	7.08 (2.26)	
	OVG	10.9 (2.92)	11.09 (2.92)	11.45 (3.00)	11.4 (2.87)	11.47 (3.17)	11.54 (3.06)	11.67 (3.39)	
Attenuation (%)	MT	60.34 (8.34)	60.86 (9.25)	62.4 (8.19)	62.54 (7.86)	62.91 (7.77)	62.72 (7.70)	62.59 (8.03)	$p < 0.001$
	cNMT	54.18 (11.86)	55.71 (10.86)	55.9 (10.50)	56.69 (10.59)	57.14 (10.62)	56.96 (9.70)	57.62 (10.7)	
	OVG	64.68 (8.86)	65.54 (8.71)	66.17 (8.54)	67.22 (8.2)	66.91 (8.86)	68.01 (8.66)	68.21 (8.87)	

MT: motorised treadmill; cNMT: curved non-motorised treadmill; OVG: overground; N.S.: Not significant. [a]difference with T1 ($p < 0.05$); [b]difference with T5 ($p < 0.05$).

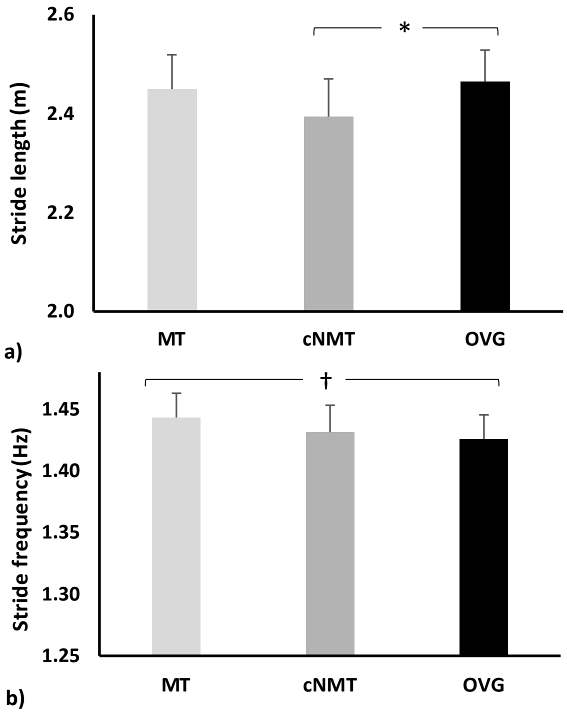

Figure 1. Spatiotemporal parameters (mean and standard deviation) average of all collected times based on the surface: a) Stride length (m), b) Stride frequency (Hz). MT: motorised treadmill; cNMT: curved non-motorised treadmill; OVG: overground; m: metres; Hz: hertz. *Statistical differences between cNMT and OVG ($p < 0.05$). †Statistical differences between MT and OVG ($p < 0.05$).

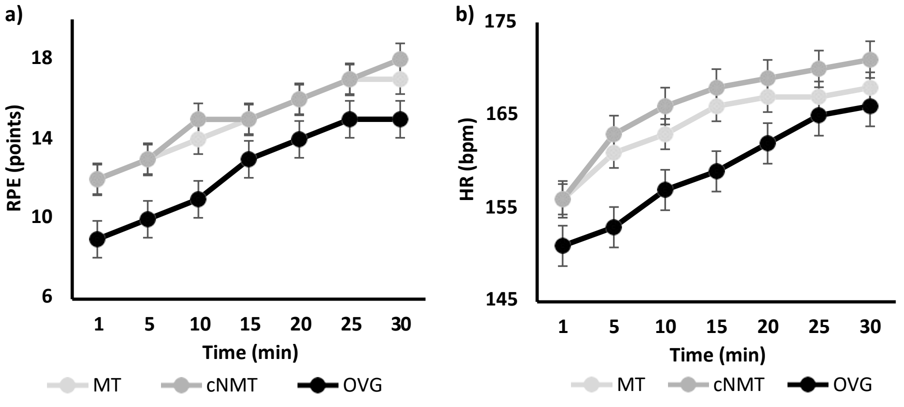

Figure 2. a) Rating of perceived effort and b) Heart rate (mean and standard deviation), based on the surface and moment of the test. MT: motorised treadmill; cNMT: curved non-motorised treadmill; OVG: overground; RPE: rating of perceived exertion; HR: heart rate.

explain this reduction: a) the pronounced forward lean of the concave belt, what favours forefoot striking instead of heel/midfoot striking (Montgomery et al., 2016), b) the altered environment of treadmill running, which force athletes to adjust the locomotion in order to reduce the risk of injury or maintain performance (Derrick, 2004) and c) the leg stiffness adjustment, which leads to different patterns of muscle activity with different neuromuscular control mechanisms and RPE (Baur et al., 2007; Montgomery et al., 2016).

The present study shows statistically significant reductions in stride length (2.9%) on cNMT and an increase in stride frequency on MT (1.2%), both compared to OVG running. However, and in accordance with Encarnación-Martínez et al. (2021) and Seneli et al. (2011), no statistically significant differences were found on spatiotemporal parameters between treadmills, although they were expected to differ due to belt friction, curvature and dimensions (Bruseghini et al., 2019). According to other studies (Caramenti et al., 2018; Reinisch et al., 1991; Riley et al., 2008), higher stride frequency and lower stride length during MT running vs OVG are due to the higher running speed perceptions experienced by runners (Milner et al., 2020), and are related to running economy. Therefore, higher stride frequencies chosen by experienced runners lead to an optimisation of energy expenditure and improvement in running economy (Hunter & Smith, 2007).

In terms of RPE and HR, cNMT generated significantly higher RPE (17.2%) and HR (3.6%) in comparison with OVG, but no differences were found between treadmills. In line with these results, previous research has suggested that cNMT increases the fatigue perception and generates greater energy expenditure compared to OVG or MT, since cNMT requires energy not only to drive the body itself, but also to propel the belt, with its own friction and slope, in every single step (Bruseghini et al., 2019; Edwards et al., 2017; Schoenmakers & Reed, 2020). Therefore, cNMT may produce a similar running pattern to OVG in comparison with MT running in terms of kinetic and kinematic parameters (Encarnación-Martínez et al., 2021; Schoenmakers & Reed, 2020). On the contrary, MT enables the runner to maintain the speed with less propulsive phase and reduces the breaking phase of gait, since the runner do not need to move backwards and forwards on the moving belt (Baur et al., 2007; García-Pérez et al., 2014; Reinisch et al., 1991).

Tibia impact accelerations are related to lower limb injuries and the risk for tibia stress fracture in distance runners (García-Pérez et al., 2013; Milgrom et al., 2003; Milner et al., 2020). Moreover, it has been suggested that a reduction in shock attenuation caused by prolonged running, running surface or injuries can damage the musculoske- letal system and increase the risk of injury (Mizrahi et al., 2000). Hines and Mercer (2004) found a reduction in shock attenuation during MT running, what could be the reason of the kinematic differences between MT and OVG (McKenna & Riches, 2007; Reinisch et al., 1991). In this study, prolonged running led to no changes ($p > 0.05$) in impact acceleration or shock attenuation, except for a decrease in head peak acceleration (MT: 1.9%, cNMT: 1.2%, OVG: 4.3%) and head acceleration magnitude (MT: 2.4%, cNMT: 1.5%, OVG: 3.9%) associated to prolonged running-related changes as runners progressed through the test (T1 vs T30). The absence of differences can be due to an insufficient running intensity or duration of the test to provoke body adaptations, being also related to running technique changes with more alterations in time-domain analysis (Encarnación-

Martínez et al., 2020). Thus, prolonged running effect may be better distinguished with other type of analysis, such as frequency-domain analysis (Encarnación-Martínez et al., 2020; Lucas-Cuevas et al., 2017). These findings are consistent with previous studies, who also found no differences in tibia acceleration after an exhausting run (Abt et al., 2011; Mercer et al., 2003); while other authors describe an increase in impact accelerations caused by prolonged running (Derrick et al., 2002; Encarnación-Martínez et al., 2020; Mizrahi et al., 2000; Verbitsky et al., 1998). Therefore, running surface can affect runners differently and force them to adopt different strategies of adaptation to fatigue.

In terms of running duration, stride frequency decreased significantly ($p < 0.05$)

during the test on MT when comparing T1 vs T30 (0.4%), however the relationship between prolonged running and spatiotemporal parameters is still unclear in the literature. Several studies affirm that prolonged running on either surface, MT and OVG, leads to an increase in stride length and to a decrease in stride frequency (Chan-Roper et al., 2012; García-Pérez et al., 2013), while others suggest the opposite (Kyröläinen et al., 2000; Vernillo et al., 2016), or even the absence of differences (Derrick et al., 2002; Fourchet et al., 2015). According to Hunter and Smith (2007), half of the participants in the study experienced a reduction in stride frequency during a 1-h high-intensity treadmill run, being this changes subject specific.

Finally, RPE (MT: 29.5%, cNMT: 33.3%, OVG: 40%) and HR (MT: 7.2%, cNMT: 8.8%,

OVG: 9.1%) increased during the run as soon as the test progressed (T1 vs T30). Therefore, running on cNMT can provoke greater perceptual demands and intensity (Edwards et al., 2017; Schoenmakers & Reed, 2018; Smoliga et al., 2015), allowing the athletes to obtain greater physiological benefits associated with moderate and vigorous exercise without any substantial increase in effort compared to MT (Smoliga et al., 2015).

There are few limitations in this study. First, participants had no previous experience running on a cNMT, which was minimised by running 8 minutes prior to the test, where the participants had enough adaptation time to this new condition. Second, only the dominant leg was analysed, while the analysis of both extremities could provide information on the symmetry of the running cycle. Future studies might investigate three-dimensional kinematics and asymmetries in lower limbs in order to identify any locomotion alterations that may be present between cNMT, MT and OVG conditions.

Conclusions

In conclusion, findings of this research suggest that not only RPE and HR but also impact accelerations and spatiotemporal parameters are different between the running surfaces studied. Running on cNMT produced a reduction in impact accelerations in comparison with MT and OVG, and MT also decreased these parameters significantly compared to OVG. Moreover, lower stride length on cNMT vs OVG and higher stride frequency on MT vs OVG were observed. On the other hand, prolonged running produced a reduction during the final stage vs the early stage of the test on MT in head peak acceleration, on cNMT in head peak acceleration, head acceleration magnitude and stride frequency and OVG in stride frequency. Finally, treadmills were considered more exhausting than OVG running, producing higher metabolic responses but no differences between them were found.

Author contributions

Research concept and study design, I.C.-V., A.E.-M. and P.P.-S.; literature review, I.C.-V. and P.P.-S.; data collection I.C.-V., and A.E.-M., data analysis and interpretation, I.C.-V., A.C.-G and A.E.-M.; statistical analyses, I.C.-V., R.S.-S. and P.P.-S.; writing of the manuscript or reviewing/ editing a draft of the manuscript, I.C.-V., A.E.-M., A.C.-G., R.S.-S. and P.P.-S.

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