The physiological and perceptual demands of running on a curved non-motorised treadmill: Implications for self-paced training

Patrick P.J.M. Schoenmakers, Kate E. Reed

Abstract

Objectives

To compare physiological and perceptual response of running on a curved non-motorized treadmill (cNMT) with running on a motorized treadmill (MT), and to determine the running velocity at which a physiological response ≥ 90% VO_2max was elicited.

Design & methods

13 trained male runners (mean ± SD; 36 ± 11 years, 1.80 ± 0.06 m, 70 ± 4 kg, VO_2max: 57.3 ± 3.5 mL kg^{-1} min^{-1}) performed an incremental running test on a MT to determine VO_2max and the accompanying maximum velocity (Vmax). Participants first completed a familiarization session on the cNMT. Next, participants ran for 4 min at five/six progressively higher velocities (40–90% Vmax). These runs were completed on the cNMT and MT in two separate visits in a randomized and counterbalanced order.

Results

No participant was able to complete the 4 min run at 80% Vmax on the cNMT. Running on the cNMT elicit a higher relative oxygen uptake (%VO_2max) across all velocities compared to the MT (32.5 ± 5%, p < 0.001, ES 3.3 ± 0.9), and was accompanied by significantly higher heart rates (16.8 ± 3%, p < 0.001, ES 3.4 ± 1.5), an altered cadence (2.6 ± 0.7%, p < 0.001, ES 0.8 ± 0.3) and ratings of perceived exertion (27.2 ± 5%, p < 0.001, ES 2.3 ± 0.6). A less efficient running economy was evident when running on the cNMT (+38.4 ± 16%, p < 0.001, ES 2.73). Individual (n = 9) linear interpolation predicted an exercise intensity of 90% VO_2max was achieved in the non-motorized condition when running at 62.1 ± 3.5% Vmax (R^2 = 0.986 ± 0.01), which was lower than MT run in which 90% VO_2 max was achieved at 81.4 ± 5.6% Vmax (R^2 = 0.985 ± 0.02; 29.8 ± 8%, p < 0.001, ES 3.87).

Conclusions

Running on the cNMT has higher physiological and perceptual demands and increases cadence.

Keywords

1. Introduction

Treadmills are an indispensable piece of laboratory equipment, and have become a key piece of exercise testing and training equipment. They are considered a valid measure of outdoor running performance, as evidenced by Jones & Doust,[1] who showed that the oxygen uptake (VO_2) during overground running and running on a motorized treadmill (MT) was strongly correlated with the use of a 1% treadmill grade. However, when performing a running task on a MT, moment-to-moment changes in velocity are not possible due to the fixed belt speed, and changes in velocity are controlled by an external motor which further requires a manual action to be changed.[2, 3] With the change of velocity controlled 'externally of the runner', deciding to change the running velocity requires a conscious decision by the runner. It is however suggested that the regulation of intensity during endurance exercise occurs unconsciously, based on live interactions with the environment and by both central and peripheral control mechanisms,[4, 5] and therefor the ecological validity of MT running may be questionable.

Recently, it has been argued that athletes measure and pace their work in training sessions in general, and in high intensity interval training (HIIT) specifically, on ratings of perceived exertion (RPE) and accumulated fatigue.[6] This *'iso-effort'* approach is in sharp contrast with protocols often used in lab based experiments, in which responses to predefined exercise intensities are studied. In self-paced HIIT, the maximum sustainable intensity is employed for a set number of work intervals of fixed durations. Athletes can then self-regulate their exercise intensity, based on their knowledge of the total volume of the session, the memory of similar events, as well as feedback from external and internal receptors.[5, 6] It is suggested that athletes should spend at least several minutes per HIIT in their 'red zone', which refers to the intensity domain close to their maximal oxygen uptake and heart rate (≥90% VO_2max and HRmax respectively).[7, 8] While self-paced HIIT has been addressed recently in cycling,[6, 9] there is a paucity of research exploring the use of self-paced HIIT in running exercise.

Previously, the acute physiological responses to self-paced running HIIT protocols of varying work durations and/or recovery durations have been studied.[10, 11, 12] However, in these studies participants ran on a MT and the velocity could be increased or decreased via a hand signal to the test administrator controlling the treadmill, highlighting the conscious external decision making process required.[10, 11, 12] Standard MTs do not allow to study the quick and frequent adjustments in running velocities that occur during self-paced exercise.[13] Non-motorized treadmills (NMT) on the other hand, are participant driven and allow runners to self-select their pace and dictate the speed of the treadmill belt with every step, which makes the overall locomotion more consistent with outdoor running.[2, 3] Previously, a commercially available curved NMT ((cNMT); Woodway Curve XL, Woodway, Waukesha, USA) demonstrated good reliability and validity for the assessment of VO_2max,[14] endurance performance,[3, 15] sprint[16] and repeated sprint intervals.[17] To evaluate the potential use of the cNMT for self-paced HIIT sessions, it is important to understand the physiological responses associated with running on the cNMT. The aim of this study therefore was to determine the physiological and perceptual demands of running on a cNMT over a range of velocities commonly used in training and races of trained runners, and compare these to the demands of running on a MT set to a 1% gradient. The second aim was to determine at which running velocity a physiological response ≥ 90% VO_2max was elicited on both the cNMT and MT. Trained club level runners were used in this study as they would likely be more attuned to internal pacing queues, and be able to maintain high workloads for sufficient time for reliable measures to be taken. It was hypothesized that the physiological demands of running on the cNMT would be higher than on a MT at any given velocity, since the curved design introduces a slight incline to the front aspect of the treadmill, which in theory demands higher energy expenditure.

2. Methods

Participants visited the sport and exercise science laboratory on 4 different occasions over a two-week period, with visits separated by at least 48 h. During their first visit, participants performed an incremental running test to voluntary exhaustion on a MT (Pulsar 3p, H/P Cosmos, Nussdorf-Traunstein, Germany) to determine VO_2max and the associated running intensity (peak treadmill velocity (Vmax)). On the second visit, participants performed the experimental running protocol (detailed below) on the cNMT as a familiarisation session (cNMTfam). Two comparative experimental sessions on the cNMT (cNMTrun) and MT (MTrun) in the third and fourth visit were performed in a counterbalanced and randomized order. All visits were completed at the same time of the day (±1 h).

Participants were asked to refrain from any strenuous exercise or alcohol consumption in the preceding 24 h, and from caffeine and food consumption, 4 and 2 h before the start of the test, respectively. Two factory calibrated treadmills were used in this study: a standard motorised treadmill, and a non-motorised treadmill with a curved surface. Accuracy of both treadmill's velocity measures were verified using a video camera and found to be within < 1.1% of the described speed. Participants were asked to report for testing wearing the same footwear on each visit.

Thirteen club level male runners (mean ±SD, 36 ± 11 years; 1.80 ± 0.06 m; 70 ± 4 kg; VO_2max: 57.3 ± 3.5 mL kg−1 min−1; Vmax: 5.0 ± 0.2 m s−1) participated in this investigation. No participant had prior experience with (curved) NMT running. Prior to their active participation, all participants provided voluntary written informed consent. The study received approval from the local ethics committee (University of Essex, UK) and was conducted in accordance with the Declaration of Helsinki.

During their first visit, participants performed an incremental running test on the MT, with the gradient set at 1%.[1] This test started at 2.22 m s^{-1}, which was increased by 0.28 m s^{-1} each minute until participants reached volitional exhaustion or when one of the following criteria was met: (1) maximal heart rate at least equal to 90% of the age-predicted maximum; (2) respiratory exchange ratio (RER) ≥ 1.1; (3) stable oxygen consumption despite increased intensity.[18] VO_2max was defined as the highest 30-s averaged VO_2 collected during the incremental test. HRmax was defined as the highest value obtained at the end of the test. Vmax was defined as the highest velocity that could be maintained for a complete minute, or as the velocity of the last complete stage added to the completed fraction of an incomplete stage. Vmax was calculated according to the equation Vmax = Vcomp + (0.28 m s^{-1} × t/60), in which Vcomp is the velocity of the last completed stage and t the time in seconds sustained during the final incomplete stage.

In the familiarisation and comparative experimental runs, participants were required to run for 4 min at five different individualized velocities (40%, 50%, 60%, 70%, 80% Vmax; velocity range [2.0 ± 0.1–4.0 ± 0.2 m s^{-1}]), with 3 min passive recovery between the 4 min runs. A subset of eight participants volunteered to complete a further (6th) running bout at 90% Vmax on the MT (velocity: 4.5 ± 0.2 m s^{-1}). In cNMTfam and cNMTrun, participants were instructed to monitor their speed on the treadmill's LCD screen and maintain it as close to the prescribed speed as possible.[3] Verbal cues to do so were provided if necessary. Average oxygen consumption, heart rate, RER and running cadence were determined during the last minute of each stage, together with overall RPE on the standard Borg scale.[19]

Running economy was calculated using the averaged VO_2 and RER from the final min of the runs conducted at 50% Vmax (2.5 ± 0.09 m s^{-1}). This speed was selected as 11 subjects completed cNMTrun and MTrun at this speed with an RER < 1.0. Running economy was expressed as gross oxygen unit cost (mL kg^{-1} km^{-1}), as well as a gross caloric unit cost (the energy required to cover a given distance; kcal kg^{-1} km^{-1}). The gross caloric unit cost was calculated as described by Fletcher et al.,[20] in which the averaged RER was used to determine the caloric equivalent of VO_2.

During the incremental running test, cNMTfam, and the two comparative experimental runs, heart rate and running cadence were measured continuously at 1 Hz using a Garmin heart rate monitor and a telemetric foot pod (910XT, Garmin Ltd., Schaffhausen, Switzerland). Respiratory parameters were measured breath by breath, using open circuit spirometry (Oxycon Delta, Jaeger, Höchberg, Germany). The gas analyser was calibrated prior to each test using room air and a calibration gas (16.0% O_2, 5.0% CO_2). The physiological measures of both VO_2 and HR were indexed for individual VO_2max and HRmax (%VO_2max and %HRmax respectively), to use these relative values as an insightful indicator of the relative exercise intensity, especially in the intense exercise domain in which VO_2 is not expected to reach steady state. Running velocity in the cNMT trials was sampled at 4 Hz, and was assessed in the accompanying product software.

Data were analysed using SPSS 23.0 (SPSS Inc., USA) and are presented as mean ± SD. Differences in running velocities were compared between cNMTfam, cNMTrun and MTrun using repeated measures ANOVAs. A comparison between cNMTfam and cNMTrun was carried out to observe any training effects due to the novelty of this piece of equipment. Repeated measures ANOVAs were carried out to compare differences between conditions (cNMTrun vs MTrun) in %VO_2, HR, RER, running cadence and RPE for each velocity. In an attempt to determine the running velocity which elicited comparable exercise intensities between the cNMT and MT, data collected during 90%

Vmax on the MT were compared with data collected during 70% Vmax cNMT (n = 8 participants) using paired t-tests. The running velocity at which the physiological response corresponded to 90% VO$_2$max was determined individually, through linear interpolation for both treadmills. Standardized effect sizes are reported as Cohen's d. Qualitative interpretation of d was based on the guidelines provided by Hopkins: <0.2 trivial; 0.20–0.59 small; 0.6–1.19 moderate; 1.20–1.99 large; ≥2.00 very large. The significance level of all tests was set at <0.05

3. Results

A summary of experimental variables is presented in Table 1. No participant was able to complete the 4 min running bout at 80% Vmax in cNMTfam or cNMTrun. No differences in running velocities were found between cNMTfam and cNMTrun (40.2 ± 0.8 vs 40.3 ± 0.8; 50.2 ± 0.6 vs 50.1 ± 0.6; 60.2 ± 0.7 vs 60.2 ± 0.7; 70.0 ± 0.6 vs 70.2 ± 0.7 for 40, 50, 60, 70% Vmax respectively, p > 0.05), or between cNMTrun and cMTrun. No learning effect was found of the familiarisation session, as no differences were apparent between cNMTfam and cNMTrun in any of the experimental variables.

Table 1
Relative oxygen uptake (%VO$_2$max), heart rate (%HRmax), respiratory exchange ratio (RER) ratings of perceived exertion (RPE) and running cadence (steps per min) in each experimental condition (n= 13 for 40–80% Vmax, n= 8 for 90% Vmax).

Running velocity	% VO$_2$max		ES	%Hrmax		ES	RER		ES	RPE		ES	Running cadence		ES
(%Vmax)	cNMTrun	MTrun		cNMTrun	MTrun		cNMTrun	MTrun		cNMTrun	MTrun		cNMTrun	MTrun	
40	64.7 ± 5.6	49.1 ± 6.6*	2.37	74.7 ± 3.6	63.8 ± 5.2*	1.84	0.93 ± 0.04	0.87 ± 0.05*	1.32	9.3 ± 1.7	7.5 ± 1.1*	1.52	162 ± 13	159 ± 8	0.43
50	76.5 ± 6.5	56.5 ± 5.5*	3.26	84.3 ± 3.3	70.9 ± 3.4*	2.78	0.97 ± 0.04	0.89 ± 0.05*	1.77	11.6 ± 1.9	9.4 ± 1.4*	2.04	167 ± 11	164 ± 9	0.47
60	88.5 ± 5.0	66.8 ± 6.1*	4.55	91.5 ± 2.7	78.0 ± 2.9*	3.74	1.02 ± 0.04	0.93 ± 0.04*	2.25	14.2 ± 1.4	11.2 ± 0.8*	2.45	172 ± 12	168 ± 9*	1.02
70	96.9 ± 4.1	77.2 ± 6.0*	2.89	96.9 ± 1.6	85.2 ± 2.4*	5.36	1.10 ± 0.04	0.97 ± 0.06*	2.55	17.3 ± 1.8	12.9 ± 0.9*	3.03	178 ± 11	172 ± 11*	1.06
80	–	87.7 ± 6.5		–	92.2 ± 2.3		–	1.02 ± 0.03		–	15.0 ± 1.2		–	178 ± 12	
90	–	97.1 ± 3.1		–	98.4 ± 1.3		–	1.09 ± 0.05		–	17.8 ± 1.1		–	190 ± 7	

NMT (non-motorized treadmill) MT (motorized treadmill), ES (effect size).
* p< 0.001 between NMTrun and MTrun.

The average oxygen uptake in cNMTrun was significantly higher at all velocities compared to MTrun (p < 0.001). On average, across the four different velocities, the oxygen consumption was 32.3 ± 4% higher in cNMTrun (see Table 1). The higher oxygen uptake was accompanied by significantly higher exercise heart rates (+16.8 ± 3%, p < 0.001) and ratings of perceived exertion (+27 ± 5%, p < 0.001). Running cadence was higher at all velocities in cNMTrun (+2.4 ± 0.8%), which reached statistical significance at 60% and 70% Vmax (p < 0.005). Differences in running economy were evident between both treadmills (see Table 2), with the economy in gross oxygen cost and in caloric cost being significantly lower in MTrun compared to cNMTrun (–38.4 ± 16%, p < 0.001, ES 2.73), indicating more economical running in MTrun.

Table 2. Runing Economy for each experimental treadmill, running on 50% Vmax (n = 11).

Running Economy:	cNMTrun	MTrun	ES
Oxygen unit cost (mL O$_2$ kg^{-1} km^{-1})	279 ± 37	206 ± 29*	2.73
Caloric Unit Cost (kcal kg^{-1} km^{-1})	1.39 ± 0.19	1.01 ± 0.14*	

cNMT (curved non-motorized treadmill) MT (motorized treadmill), ES (effect size).

* p < 0.001 between cNMTrun and MTrun.

Table 3 shows data comparing 70% Vmax cNMT and 90% Vmax MT (n = 8). Apart from a significantly higher cadence in MTrun (p = 0.001), there were no differences in physiological or psychological responses. All thirteen participants reached an exercise intensity of ≥ 90% VO$_2$max in NMTrun. Linear interpolation of the available data in cNMTrun predicted an exercise intensity of 90% VO$_2$max was achieved when running above 62.7 ± 3.3% Vmax (R^2 = 0.986 ± 0.01). Nine out of the thirteen participants reached 90% VO$_2$max in MTrun, at a running velocity of 81.4 ± 5.6% Vmax (R^2 = 0.985 ± 0.02), which was significantly higher (p < 0.001, ES 3.87).

Table 3. Comparison of relative oxygen uptake (%$\dot{V}O_2$ max), heart rate (%HRmax), respiratory exchange ratio (RER), ratings of perceived exertion (RPE) and running cadence (Steps per min) between 70% Vmax cNMTrun and 90% Vmax MTrun (n = 8).

	Running velocity		
	70% Vmax cNMTrun	90% Vmax MTrun	ES
% $\dot{V}O_2$max	97.9 ± 3.8	97.1 ± 3.1	0.18
% HRmax	97.0 ± 1.5	98.2 ± 1.5	0.35
RER	1.10 ± 0.04	1.09 ± 0.05	0.45
RPE	17.5 ± 1.7	17.8 ± 1.2	0.95
Cadence	182 ± 6	190 ± 8[*]	1.82

cNMT (curved non-motorized treadmill) MT (motorized treadmill), ES (effect size).

[*] p < 0.01 between cNMT and MT.

1. Discussion

Non-motorized treadmills allow runners to adjust their running velocity subconsciously, consistent with outdoor running, and thus may be more appropriate apparatus to study self-paced training. This study aimed to (1) determine the physiological and perceptual demands of running on a curved NMT over a range of velocities, and (2) verify at which running velocity a physiological response ≥ 90% VO$_2$max was elicited.

When running on a NMT, participants must generate power to move themselves vertically and to propel the treadmill belt,[21] which the manufacturer claims to result in a 30% higher caloric expenditure compared to running on a standard MT. Part of this higher energy expenditure may be due to a range of cNMT characteristics (e.g. a high mechanical resistance and rubber material of the treadmill belt), and may be inherent to the treadmill design. Findings of the current study support the manufacturers claim, as VO$_2$ was, on average 32.2 ± 4% higher in NMTrun across the different velocities. Furthermore, an increase in caloric cost of 38.4 ± 16% was evident when participants ran at 50% Vmax (1.39 ± 0.19 vs 1.01 ± 0.14 kcal kg^{-1} km^{-1} for cNMT and MTrun respectively). These results are in line with Smoliga et al.,[22] who showed that walking (1.34 m s^{-1}) and running (2.24 m s^{-1}) on the cNMT elicits a greater physiological stimulus than that on MT. The running velocity of 2.24 m s^{-1} used by Smoliga et al.[22] corresponds to 45% Vmax of the participants in the current study. This study aimed to evaluate the physiological responses to a broader range of (higher) running velocities, and, additionally, attempted to identify the running velocity that elicits an exercise intensity ≥ 90% VO$_2$max on both treadmills. Linear interpolation showed this intensity was achieved when running at 62.7 ± 3.3% Vmax on the cNMT. Similar exercise intensity was reached in nine out of thirteen participants on the MT at 81.4 ± 5.6% Vmax. The difference in %Vmax for the nine participants that reached ≥ 90% VO$_2$max in both NMTrun and MTrun was 19.1 ± 5.1%. This is similar to the findings of Stevens et al.[3] and Waldman et al.,[15] who both reported that 5 km running performance on the curved NMT was significantly slower compared to overground running (22%)[3] and MT running (24%),[15] even though no differences in VO$_2$ and exercise heart rates were found. In another recent study, Morgan et al.[14] observed a significant 15% lower Vmax on cNMT compared to a MT during an incremental running tests, where again, the participants were exerting the same exercise intensity in both tests. The large differences in running velocities while exercising at comparable exercise intensities highlights the disparity between the two treadmills.

The nature of the cNMT is such that users are required to run on an uphill gradient. To increase running velocity, participants position their feet closer to the front of the curved belt, which allows a

greater contribution of vertical force to treadmill belt propulsion. Curved treadmill belts may facilitate a more natural gait pattern, allowing increased stride length and longer swing phase, which is observed with over-ground locomotion. Observational analysis by Smoliga et al.,[22] revealed that subjects contact the curved treadmill belt approximately at a five to ten degree incline above the horizontal and this angle decreases throughout the stance phase of the stride cycle. It has been suggested that runners always optimise their technique to minimise metabolic costs, and when an inclination is present, runners will modify mechanical variables to achieve optimal metabolic efficiency.[23] Stevens et al.,[3] reported a change in running technique between overground and cNMT running. In overground running their subjects (n = 10) were classified as predominantly 'rear-foot strikers' (9, 1 "mid-foot strike"), which in cNMT running changed to "mid-foot strike" (8, 2 'rear-foot strikers'). The change in running technique was further evident in changes in muscle recruitment patterns between cNMT and over-ground running, as they showed a decline in iEMG activity for tibialis anterior, vastus lateralis and rectus femoris in the former.[3] The decrease in iEMG is most likely compensated with an increased EMG activity of the gluteus maximus and bicep femoris while running uphill.[24] In line with previous research, an increase in energy expenditure, and running cadence was found in cNMTrun compared to MTrun during all experimental velocities,[23, 25] highlighting the uphill running character of the cNMT. Recently, several studies have examined the effects of a variety of uphill HIIT protocols, using repeated short (6–30 s) and/or long (3–5 min) work intervals on a variety of treadmill gradients.[26, 27] These studies showed improvements in various physiological, biomechanical, and neuromuscular parameters relevant to running performance, and provide support to incorporate uphill HIIT in the training programs of distance runners. Future research is needed to evaluate which treadmill gradient is most comparable to the curved design of the NMT, in aid to design the most appropriate training intervention. Self-paced uphill HIIT is a promising focus area for future research, and the cNMT allows evaluation of physiological responses in a well-controlled lab setting.

In the current study VO_2max and Vmax were determined using a traditional incremental running test, performed on a MT. The obtained VO_2max was then used to compute and compare the relative oxygen uptake between cNMTrun and MTrun on different individualized running velocities. It is well known that VO_2max is dependent on the physiological conditions present during an exercise protocol,[18] and it has been shown that a self-paced VO_2max test performed on a NMT could possibly result in an elevated VO_2max.[28] In fact, VO_2 in three of the thirteen participants was higher in cNMTrun while running at 70% Vmax than reached during their incremental running test. Conversely, Morgan et al.,[14] found no differences in attained VO_2max or maximum heart rate between MT and the cNMT. Thus, the increased VO_2 in those few individuals in the current study may be attributed to the difference in bout duration between the experimental runs (4 min) and stage length in the incremental exercise test (1 min), rather than the different treadmills. VO_2 continued to increase at 70% Vmax in NMTrun, showing 'oxygen drift'. Oxygen drift is potentially caused by increased muscle fibre recruitment, changes in efficiency, body temperature and the increase of muscle fatigue over time, which all contribute to a larger amplitude in the slow component of VO_2.[29] The increased contribution of this slow component of VO_2 likely elevated the oxygen uptake in the 4 min run.

A limitation of this study is the inability to state the anaerobic contrition to metabolic work during the higher intensity intervals. When RER exceeds 1.0 the energetic cost of the exercise is more difficult to estimate, and it is not possible to compare energetic cost across individuals or across trials.

The results of the present study further information in the field of NMT running, by providing comparison velocities at which physiological workload is matched. Participants in the current study ran at higher and individualized velocities compared to previous studies, which yield new insights into the physiological and perceptual responses in the intense exercise domain. Only a subgroup (n = 8) opted to complete the 90% Vmax run, and this would have had implications related to statistical power.

Practical applications

- The cNMT can be a useful tool to study self-paced interval training. When prescribing exercise specialists often assign a specific (treadmill) velocity and duration as the primary training variables. Our data show that exercise prescriptions that are appropriate for over-ground or MT running may not be achievable on the cNMT because of the differences in energetic requirements.

- Based on our results, it is advised to lower the running velocity by 20% when running on the cNMT to generate the comparable physiological stimulus.

- Running on the cNMT mimics uphill running, and therefore training adaptations may differ compared to over-ground or regular treadmill training.

Author contributions

PS and KR contributed to conception and design of the work. PS conducted the experiment, analyzed the data and wrote the first draft. Both authors were involved in further data analysis and drafting, and revized the manuscript critically for important intellectual content.

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