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Metabolic and kinematic responses while walking and running on a motorised and a curved non-motorised treadmill

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Metabolic and kinematic responses while walking and running on a motorised and a curved non-motorised treadmill

Running title: Metabolic and kinematic responses on a curved non-motorised treadmill

Abstract

The purpose of this study was to assess metabolic and kinematic parameters (contact and flight time, step length and frequency) while walking at the preferred speed (1.44 ± 0.22 m·s^{-1}) and while performing an incremental running test (up to exhaustion) on a motorised treadmill (MT) and on a curved non-motorised treadmill (CNMT). Twenty-five volunteers (24.1 ± 3.4 years; 64.7 ± 11.2 kg) participated in the study. Maximal running speed on MT was significantly larger ($P<0.001$) than on CNMT (4.31 ± 0.50 vs. 3.75 ± 0.39 m·s^{-1}) but no differences in heart rate or oxygen uptake ($\dot{V}O_2$) were observed at this speed. The energy cost of walking (C_w) and running (C_r) were significantly greater ($P<0.001$) on CNMT than on MT (37% and 17%, respectively). No major differences in kinematic parameters were observed at paired, submaximal, running speeds (2.22-3.89 m.s^{-1}) but $\dot{V}O_2$ was systematically larger in CNMT (of about 340 mL·min^{-1}·kg^{-1}). This systematic difference can be expressed in terms of a larger "equivalent speed" on CNMT (of about 0.42 m·s^{-1}) and should be attributed to factors other than the kinematic ones, such as the belt characteristics (e.g. friction, type of surface and curvature).

Keywords: curved non-motorised treadmill; energy cost of running; energy cost of walking; kinematics; belt friction.

Word count: **3885**

Introduction

Walking or running on a treadmill is a popular way to perform aerobic exercise in different populations, from disabled patients undergoing rehabilitation to elite athletes for training or testing purposes. Traditionally, two forms of flat treadmills are available to consumers: motorised and non-motorised. Recently, a new non-motorised treadmill design with a concave curved surface (CNMT) has been introduced. This device was designed in such a way that the user controls the treadmill belt speed dynamically by changing the position where he/she walks or runs. The treadmill manufacturer suggests that exercise performed on this curve surface can elicit a larger energy expenditure, at matched speeds, than when exercising on a flat, motorised treadmill (MT). Indeed, Edwards, Tofari, Cormack & White (2017) suggested that the higher fatigue perceived while using this type of treadmill has to be attributed to the higher energy requirement needed not only to propel the body, but also to propel the belt.

Despite the growing popularity of non-motorised treadmills, the evidence regarding the exercise responses when using these devices is still scarce. Whereas some studies have analysed kinematic data (Seneli, Edlbeck, Myatt, Reynolds, & Snyder, 2011; Waldman, Heatherly, Waddell, Krings, & O'Neal, 2017), muscular adaptations (Franks, Brown, Coburn, Kersey, & Bottaro, 2012; Mangine et al. 2014; Mangine et al. 2015) and foot mechanical stress (Snyder, Edlbeck, Myatt, & Reynolds, 2011), other studies focused mainly on the metabolic responses (Edwards, Tofari, Cormack & White, 2017; Gonzalez et al., 2013; Highton, Lamb, Twist, & Nicholas 2012; Morgan, Laurent, & Fullenkamp, 2016; Stevens, Hacene, Sculley, et al., 2015). Moreover, in some studies only submaximal exercise intensities were investigated (Edwards, Tofari, Cormack & White, 2017; Seneli, Edlbeck, Myatt, Reynolds, & Snyder; 2011; Smoliga, Hegedus, & Ford, 2015) whereas in others the focus was on the metabolic responses at maximal speed (Morgan, Laurent, & Fullenkamp, 2016; Stevens, Hacene, Sculley, et al., 2015).

Taken together, these studies have shown that CNMT elicits greater physiological responses than MT at matched submaximal speeds, without significant differences in the kinematic parameters. At maximal speed it is, however, possible to reach similar metabolic responses (i.e. the same peak oxygen consumption and maximal heart rate) with both devices, albeit at slightly different running speeds. Some studies (Edwards, Tofari, Cormack & White, 2017; Snyder, Myatt, Weiland, Bednarek, & Reynolds, 2010) have suggested that the elevated metabolic demand (and the higher fatigue perceived) on CNMT is attributable to the treadmill belt friction since, when exercising on this treadmill, energy is required not only to propel the body, but also to propel the belt.

Therefore, the aim of this study was to assess, in the same subjects, kinematic and metabolic data while walking and running (at submaximal and maximal speeds) on a CNMT and to compare these data with those, assessed at the same speeds, on a MT in order to get a comprehensive picture of the reason of the differences observed in the literature between these treadmill types. Moreover, in this study we determined the CNMT belt friction in the attempt to quantify its metabolic effect in all the above-mentioned exercise conditions.

Materials and methods

Subjects

Twenty-five (10 men and 15 women) regularly active individuals (age: 24.1±3.4 years; body mass: 64.7±11.2 kg; stature: 1.71±0.09 m) were recruited by local advertisements at the School of Sport and Exercise Sciences of the University of Verona (Italy). All subjects completed a PAR-Q assessment and underwent a preliminary medical examination to exclude diseases contraindicating exercise (American College of Sports Medicine, 2014). The investigation was conducted in accordance with the ethical standards of the Declaration of Helsinki and was approved by the authors' institutional review board (approval on February 11th 2016). Written informed consent was obtained from each volunteer.

Experimental approach to the problem

Two treadmills were utilised for this study: 1) MT (h/p/cosmos Saturn® 300/100, Nussdorf-Traunstein, Germany); and 2) CNMT (Curve 3.0™, Woodway, Waukesah, US). Subjects came to the laboratory on five separate occasions. To improve test reliability, as suggested by Gonzalez et al. (2013), during the first three visits they performed familiarization sessions on the two treadmills at different and randomised walking and running speeds (about 20 min for each session, i.e. about 10 min for each treadmill) during which detailed verbal instructions were provided about the testing protocol. During the third session, each participant completed a 3 min walking test to detect his or her preferred walking speed (PWS) on CNMT. In this occasion PWS was freely chosen, without verbal or visual feedback; this speed was recorded and then proposed during the first step of the incremental test on both CNMT and MT. Following the three familiarization visits, participants reported to the laboratory on two separate days. To minimize any ordering effect, the participants were randomly assigned to perform either incremental test on MT or CNMT. The two visits were separated by 72 hours and were conducted at the same time of the day (±1 hours). In the 48 hours preceding the test, the subjects were instructed to refrain from strenuous exercise and to maintain the same eating habits.

Exercise protocol

Each participant performed a maximal incremental exercise test on both MT and CNMT consisting of: i) 3 min at rest (standing on treadmill); ii) 3 min of warm-up at PWS, iii) steps where speed was increased by 0.28 $m \cdot s^{-1}$ (e.g. 1 $km \cdot h^{-1}$) each minute (starting from 1.67 $m \cdot s^{-1}$) until voluntary exhaustion. The speed on MT was automatically increased by using MT software, whereas the speed on CNMT was adjusted by the participant "on command": verbal feedback on speed was provided to the participant by a technician who monitored the speed output in real time using a customised software (Curve Software, Version 1.32; World Wide Software Solutions Inc., Milwaukee, USA) in order to maintain the target speed. Speed data on CNMT were averaged every 1-min in each completed stage. Throughout the tests, oxygen uptake ($\dot{V}O_2$), heart rate (HR), minute ventilation ($\dot{V}_E$) and respiratory exchange ratio (RER) were recorded continuously using a metabolic cart. Rating of perceived exertions (RPE) were recorded during the final 15 seconds of each stage by asking the subjects to select the level of perceived effort on a Borg CR-10 scale presented by the operator. Before the exercise and 1, 3, 5 and 7 min after the end of exercise, a blood sample was collected from the ear lobe and analysed for lactate concentration ([La]) (Biosen C-line, EKF diagnostic GmbH, Barleben, Germany); the highest of the four readings was taken as peak lactate value: $[La]_{peak}$.

Anthropometric measurements

Body mass and stature were taken with a Tanita electronic scale BWB-800 MA (Tanita Corporation, Tokyo, Japan) and a stadiometer (Holtain Ltd., Crymych, Pembs. United Kingdom)

Metabolic measurements

Breath-by-breath gas exchanges and $\dot{V}_E$ at the mouth were measured during the tests by using a metabolic cart (Quark b^2, Cosmed, Rome, Italy). HR was recorded by means of short-distance telemetry embedded in the metabolic cart. Before each test, the gas analyzers and the turbine flow meter were calibrated, following the manufacturer's instructions, by using a gas mixture of known and certified concentrations (FO_2: 0.16; FCO_2: 0.05; N_2 as balance) and a 3.0-litre calibrated syringe. All parameters were recorded as the mean of the values occurring in the last 30 seconds of each 1-min step at constant speed. Gas exchange threshold (GET) was determined by means of the V-slope approach (Beaver, Wasserman, & Whipp, 1986) after a preliminary smoothing obtained by applying a three-sample moving average. $\dot{V}O_{2peak}$ values were reported as the highest 30 sec value observed during the final minute of the incremental test.

Energy cost of locomotion

The net energy cost of walking (C_w) at PWS was calculated as the ratio between net oxygen consumption ($\dot{V}O_2$ net = $\dot{V}O_2$ at steady state – $\dot{V}O_2$ at rest) and walking speed, (s):

$$C_w = \dot{V}O_{2net} / s$$

when $\dot{V}O_{2net}$ is expressed in $ml \cdot min^{-1} \cdot kg^{-1}$ and s in $m \cdot min^{-1}$, C_w units are $ml \cdot m^{-1} \cdot kg^{-1}$. C_w was then expressed in $J \cdot m^{-1} \cdot kg^{-1}$ by taking into account the appropriate energy equivalent ($J \cdot ml^{-1}$; corrected for the RER) (e.g. Garby & Astrup 1987). The net energy cost of running (C_r) was calculated as the slope (b) of the linear relationship between $\dot{V}O_2$ and running speed (s):

$$(\dot{V}O_2 = a + bs)$$

$$C_r = \Delta\dot{V}O_{2net} / \Delta s$$

When $\dot{V}O_2$ is expressed in $J \cdot min^{-1} \cdot kg^{-1}$ and s in $m \cdot min^{-1}$, C_r units are $J \cdot m^{-1} \cdot kg^{-1}$ (see Figure 1). This method to calculate C_r during an incremental running protocol was proposed by di Prampero, Salvadego, Fusi, & Grassi (2009), to which the reader is referred for further details. It suffice here to say that, as proposed by these authors, $\dot{V}O_2$ was averaged over the last 30 s of each step (see above) and that only data below GET were taken into account; moreover, only data where duty factor (DF) > 0.5 (e.g. running gait) were considered for these calculations. In Figure 1 an example of these calculations is reported for a typical subject: the slope of these linear relationships (C_r) is larger when running on CNMT (4.56 $J \cdot m^{-1} \cdot kg^{-1}$) than on MT (3.50 $J \cdot m^{-1} \cdot kg^{-1}$). Average r^2 for the individual linear C_r vs. s relationships was 0.988 ± 0.012 (for MT) and 0.984 ± 0.013 (for CNMT).

****Figure 1 near here****

Kinematic measurements

Each experiment was recorded with a digital camera (Nikon, Coolpix S5100, Japan, 120 frames/s) located on a 0.7 m high tripod, at a 3 m distance from the running lane, and perpendicular to the subjects' sagittal plane. The videos were analysed by means of an open-source software (Tracker, physlets.org, version 4.95). During the PWS and at all speeds of the incremental test, the following variables were recorded: step frequency (SF, $steps \cdot s^{-1}$), contact time (CT, s), flight time (FT, s) and step length (SL, m); SL was calculated by dividing the average speed by the step frequency (since s = SF·SL). DF was calculated as the fraction of the time spent in contact with the ground (CT) over total cycle time (CT+FT); when this value is larger than 0.5 it indicates that the subject is walking, when lower than 0.5 it indicates that the subject is running.

Belt friction

A subject was asked to run on CNMT up to a speed of about 5 $m{\cdot}s^{-1}$ and then to jump off the belt by pushing himself upwards on the handlebars. The decrease in belt speed as a function of time (data were sampled every 1 s) as determined in 14 trials is reported in Figure 2: $s = 5.203 - 0.304{\cdot}t$, $r^2 = 0.969$. The slope of this relationship is the belt deceleration: -0.304 $m{\cdot}s^{-2}$. By knowing the mass of the treadmill belt (29 kg, according to manufacturer data), belt friction (F_b) was calculated ($F_b = m{\cdot}a$) and found to be equal to 8.81 N.

****Figure 2 near here****

Statistical analysis

In text and tables data are reported as means ± SD. Data collected at PWS, GET and maximal speed (e.g. at $\dot{V}O_{2peak}$) (see Table 3) were compared by means of a one-way ANOVA (treadmill type effect). Data of energy cost of walking and running on the two treadmills were compared by means of a paired t-test. The duration of the incremental test was different for different subjects (according to their physiological characteristics) and, in several cases, the same speed attained on MT could not be sustained on CNMT. For these reasons, to analyse data collected during the incremental test, only data at paired speeds were considered (i.e. if a given speed on MT was not sustained also on CNMT these data were not taken into account): for this analysis we took into consideration only speeds from 1.67 to 4.17 $m{\cdot}s^{-1}$ (see Tables 1 and 2). On these data, a two-way ANOVA was performed (speed x treadmill type effects); post hoc tests were carried out by using Bonferroni test for pairwise comparisons. The decrease of belt speed as a function of time (for the determination of belt friction), as well as the relationships between $\dot{V}O_2$ and speed (for the determination of C_r) were examined using

Pearson correlation coefficients. Significant level was set at $P < 0.05$; statistical analysis was carried out using SPSS 24.

Results

In Tables 1 and 2 the kinematic and metabolic data collected during the incremental test are reported. All participants were able to run up to 2.78 $\text{m}\cdot\text{s}^{-1}$ on both treadmills, only 6 of them were able to sustain a speed of 4.17 $\text{m}\cdot\text{s}^{-1}$ on both MT and CNMT. Kinematic data (Table 1) were all dependent on treadmill speed ($P < 0.001$, main effect), but only FT ($P = 0.045$) and SF ($P = 0.044$) differed between the two treadmills. A significant interaction was found between the type of treadmill and running velocity only ($P = 0.005$); post hoc tests revealed a significant difference in speed between MT and CNMT at 2.22, 2.50 and 4.17 $\text{m}\cdot\text{s}^{-1}$. The differences in speed, however, were rather low in absolute terms (on the order of 0.03 $\text{m}\cdot\text{s}^{-1}$, e.g. 10% of the difference in speed between steps); we can thus assume that the differences in metabolic parameters observed between treadmills are not attributable to differences in speed but, rather, to the treadmill type itself.

****Table 1 near here****

Metabolic data (Table 2) were all dependent on treadmill speed ($P < 0.001$, main effect) but also on treadmill type ($P < 0.001$, main effect): walking or running on CNMT elicited larger metabolic responses than walking or running on MT. A significant interaction (treadmill-velocity) was found for $\dot{V}_E$, RER and RPE data; post hoc tests revealed that the interaction was significant for $\dot{V}_E$ at all speeds, for RER at all speeds but not at 1.67 $\text{m}\cdot\text{s}^{-1}$, and for RPE at speeds of 1.94, 3.33, 3.61 and 3.89 $\text{m}\cdot\text{s}^{-1}$.

****Table 2 near here****

In Table 3 data collected at PWS, GET and at maximal speed are reported. At PWS, significant differences were observed in SL (*P* = 0.045) and SF (*P* = 0.037) between MT and CNMT, whereas at maximal speed significant differences were observed in FT (*P* = 0.036), SF (*P* = 0.031) and speed (*P* < 0.001). Regarding metabolic data, i) at PWS no significant differences in speed and in RPE were observed, but metabolic parameters were all significantly larger in CNMT than in MT (0.001< *P* <0.01); ii) at GET running speed was significantly lower in CNMT than in MT (*P* < 0.001) and significant differences were observed in $\dot{V}_E$ (*P* = 0.014), RER (*P* < 0.001) and RPE (*P* < 0.006); iii) at maximal speed the speed was significantly lower in CNMT than in MT (*P* < 0.001) and significant differences were observed in RER (*P* < 0.001).

$[La]_{peak}$ at the end of ramp test was significantly higher (*P* = 0.016) in CNMT than in MT (10.86 ± 2.76 $mmol^{.}L^{-1}$ and 9.02 ± 2.47 $mmol^{.}L^{-1}$, respectively).

****Table 3 near here****

In Figure 3 the average values (±SD) of energy cost of walking (at PWS) and running are reported for MT (white columns) and CNMT (gray columns) (C_w CNMT: 3.78 ± 0.35 $J\cdot kg^{-1}\cdot m^{-1}$; C_w MT: 2.43 ± 0.39 $J\cdot kg^{-1}\cdot m^{-1}$; C_r CNMT: 4.79 ± 0.99 $J\cdot kg^{-1}\cdot m^{-1}$; C_r MT: 4.01 ± 0.58 $J\cdot kg^{-1}\cdot m^{-1}$). Larger values were observed in CNMT compared to MT (*P* < 0.001), the energy cost of walking on the curved treadmill being similar to that of running on a motorised one (*P* = 0.11).

****Figure 3 near here****

In Figure 4 the $\dot{V}O_2$ values assessed during the incremental running test are reported as a function of running speed (in the 2.22-3.89 $m \cdot s^{-1}$ speed range, where DF < 0.5, as in running) for MT (open circles) and CNMT (open squares); this figure indicates that, at paired speeds, the difference between the $\dot{V}O_2$ values is constant (it amounts to 340 ± 27 $ml \cdot min^{-1} \cdot kg^{-1}$, see data reported in Table 1). The black squares in this figure represent the CNMT values shifted, on the x-axis, of 0.42 $m \cdot s^{-1}$: they are superimposed to the MT values.

****Figure 4 near here****

Discussion

The purpose of this study was to examine the metabolic demands, the energy cost and the kinematic parameters while walking at PWS or while running during an incremental test to exhaustion performed on a MT and a CNMT. We furthermore attempted to quantify the energy required to overcome belt friction during exercise performed on CNMT.

The main findings of this study are: i) no major differences in physiological variables were observed at maximal running speed (but for lactate concentration and RER); maximal speed was, however, larger on the MT than on the CNMT; ii) the energy cost of walking and running (at submaximal speeds) is larger on the CNMT than on the MT; iii) the larger energy expenditure in walking can be, partially, attributed to kinematic differences (in SL and SF) between treadmills; iv) the larger energy expenditure in running can not be attributed to differences in kinematic variables (that did not differ between treadmills at paired submaximal speeds): it could be attributed to belt friction (or, in more general terms, to differences in the belt characteristics between the treadmills); v) the "belt effect" can be quantified either in terms of a larger $\dot{V}O_2$ at paired running speed or in terms of larger "equivalent speed" on CNMT compared to MT.

Kinematics

Kinematic parameters can be expected to differ between treadmills, because of differences in belt friction and curvature (larger on CNMT) as well as in belt dimensions (larger belt width and length on MT). Fullenkamp, Tolusso, Laurent, Campbell, & Cripps (2017) suggested that CNMT alters the biomechanical features of walking and running compared to MT or over ground exercise. Seneli et al. (2011) analysed some biomechanical parameters at different speeds on CNMT and MT, but they did not find any difference in step length between treadmills. Conversely, Waldman et al. (2017) showed some differences in the stride length and cadence during 5-km time trial tests performed on MT and on CNMT, without significant differences in metabolic responses. We observed differences in SL and SF when walking at PWS but no differences in kinematic variables at submaximal, paired, running speeds (see Table 3); this suggests that the (comparatively larger) differences in the metabolic responses between treadmills should be attributed to other factors (than kinematic ones).

Energy expenditure

Submaximal speeds

Data collected in this investigation confirmed that it is more intense to walk and run (at submaximal speeds) on a CNMT than on a MT (see Table 2), as the net C_w and C_r were higher on CNMT compared with MT. The differences between treadmills are in line with those reported in literature during walking or running at comparable speed by using similar treadmills. Smoliga et al. (2015) compared physiological and perceptual responses when walking and running on a CNMT and a MT at the same speeds (walking: 1.34 m·s^{-1}; running: 2.24 m·s^{-1}) and found that energy expenditure was higher when walking and running on a CNMT. As previously found by Wee, Von Heimburg, & Van Den Tillaar (2016) we observed that physiological variables showed significant differences between treadmills at all submaximal speeds.

Some studies suggested that the larger metabolic cost on a non-motorised treadmill is mainly caused by the fact that the runner has to produce an extra force to re-accelerate the belt mass and induce belt rotation (Snyder, Myatt, et al., 2010; Snyder, Weiland, et al., 2010; De Witt et al. 2009). We estimated the force needed to rotate the treadmill belt (8.81 N) and we quantified the effects that this force could have on exercise intensity when running on a CNMT: a larger $\dot{V}O_2$ at paired running speed (of about 340 ml·min^{-1}·kg^{-1}) or a larger "equivalent speed" (0.42 m·s^{-1}) compared to MT.

Interestingly, Morgan et al. (2016) found a similar $\dot{V}O_2$ difference between a CNMT (the same we utilised in this study) and a motorised treadmill (different from the one utilised in this study); in a speed range (4.0-8.0 mph = 1.8-3.6 m.s^{-1}) similar to that considered in our study (2.2-3.9 m.s^{-1}) the $\dot{V}O_2$ difference at paired speed is almost constant and of about 420 ml·min^{-1}.

In walking, the difference in $\dot{V}O_2$ between MT and CNMT is larger (about 400 and 550 ml·min^{-1}·kg^{-1} at PWS and 6 m·s^{-1}, respectively) than in running at submaximal speeds (about 340 ml·min^{-1}·kg^{-1}) and thus factors other than belt friction could be expected to play a role. Indeed, at PWS some differences in SL and SF were observed; moreover, maintaining a constant speed on a CNMT, at slow walking speeds, probably requires a continuous adjustment of stride rate and/or stride length and this, in turn, may require a greater neuromuscular activation of the locomotory muscles than exercising on a MT (Smoliga et al., 2015).

It is interesting to note that a larger % difference in the energy cost of walking compared to that of running was also observed when exercising on a treadmill with an even or uneven surface (Voloshina & Ferris 2015): 27% vs. 5% in walking and running respectively. In our study the differences in C are of about 37% and 17%, in walking and running respectively. As discussed by these authors, in running humans tend to prefer narrow step widths (closer to the midline of the body) and this reduces the lateral moments about the centre of mass and tends to reduce the energy cost compared to larger step widths (as in walking). Caution is thus required when comparing the metabolic responses among different treadmills (Smith et al. 2017) since they could differ based on belt curvature, friction, stiffness, and surface (uneven or smooth).

Maximal speed

$\dot{V}E$, HR and $\dot{V}O_2$ values at maximal speed on CNMT were similar to those assessed on MT in agreement with previous studies (Morgan at al. 20016, Wee et al., 2016) even if maximal running speed was significantly larger on MT. RER and $[La]_{peak}$ were significantly higher at the end of the incremental test on CNMT, indicating that running on this treadmill was more metabolically demanding. To our knowledge no data are reported in the literature about $[La]_{peak}$ on CNMT. However, Wee et al. (2016) showed that [La], at a sub maximal speed of 16 $km \cdot h^{-1}$, is much lower on MT than on CNMT (4 vs. 10 $mmol \cdot L^{-1}$ on MT and CNMT, respectively).

Practical application

The increased energy expenditure at paired walking and sub-maximal running speeds on the CNMT could have implications for populations that cannot achieve high running speeds. For obese persons, people with locomotory diseases or returning from injury, walking or jogging on the CNMT elicits larger energy expenditure than on a traditional MT at any given speed. The energy demand on a CNMT is, however, closely linked to its mechanical characteristics (curvature, friction and type of surface) and this must be taken into account in exercise prescription.

Conclusions

At submaximal speeds walking and running on a CNMT elicits greater physiologic responses than walking and running on a MT, as indicated by the greater C_w and C_r. The increased physical effort while exercising on a CNMT can be attributed to the mechanical characteristics of the belt and only to a minor extent to changes in the walking and running pattern.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Figure legend:

Figure 1. Oxygen uptake ($\dot{V}O_2$), expressed in $J \cdot min^{-1} \cdot kg^{-1}$, as a function of speed, expressed in $m \cdot min^{-1}$, in one subject running on CNMT (full dots) or MT (open dots). The slope of these relationships is a measure of the energy cost of running ($C_r = \Delta\dot{V}O_2 / \Delta v = J \cdot m^{-1} \cdot kg^{-1}$) in these two conditions: C_r (MT) = $3.50 \cdot s - 25.23$, $r^2 = 0.994$; C_r (CNMT) = $4.56 \cdot s – 9.48$, $r^2 = 0.995$. As shown in this figure, the regression lines were drawn disregarding the values collected at the two slowest speeds of the incremental test (1.67 and 1.94 $m \cdot s^{-1}$, where DF > 0.50) and the values above GET (gas exchange threshold). See text for details.

Figure 2. Average values (± SD) of belt speed as a function of time (t) in the tests to determine belt friction (each data point represents the average of 14 measurements). The slope of the dotted line represents the belt deceleration ($a = \Delta s / \Delta t$). See text for details.

Figure 3. Average values (± SD) of energy cost of walking at PWS and energy cost of running for MT (white columns) and CNMT (gray columns). (#) Significant difference ($P < 0.001$) between MT and CNMT.

Figure 4. $\dot{V}O_2$ values as a function of running speed for MT (open circles) and CNMT (open squares) during the incremental test; when $\dot{V}O_2$ data for CNMT are shifted, on the x-axis, of 0.42 $m \cdot s^{-1}$ (black squares) they result superimposed to the MT values. See text for details.

Table 1. Kinematic data during the incremental test

Target Speed		Real Speed		CT		FT		SF		SL		DF	
		m▪s^{-1}		s		s		steps▪s^{-1}		m		---	
m▪s^{-1}	n°	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT
1.67	25	1.67 ± 0.00	1.67 ± 0.06	0.59 ± 0.04	0.60 ± 0.04	0.38 ± 0.03	0.38 ± 0.03	1.0 ± 0.1	1.0 ± 0.1	0.81 ± 0.05	0.81 ± 0.06	0.60 ± 0.05	0.61 ± 0.01
1.94	25	1.94 ± 0.00	1.92 ± 0.06	0.56 ± 0.05	0.57 ± 0.05	0.36 ± 0.03	0.36 ± 0.03	1.1 ± 0.1	1.1 ± 0.1	0.90 ± 0.07	0.89 ± 0.07	0.60 ± 0.05	0.62 ± 0.01
2.22	25	2.22 ± 0.00	2.25 ± 0.06*	0.37 ± 0.04	0.37 ± 0.04	0.08 ± 0.02	0.07 ± 0.02	2.3 ± 0.3	2.3 ± 0.2	0.98 ± 0.11	0.98 ± 0.09	0.45 ± 0.01	0.46 ± 0.01
2.50	25	2.50 ± 0.00	2.47 ± 0.06*	0.33 ± 0.03	0.33 ± 0.03	0.09 ± 0.02	0.08 ± 0.02	2.4 ± 0.2	2.4 ± 0.3	1.04 ± 0.09	1.04 ± 0.10	0.44 ± 0.01	0.44 ± 0.01
2.78	25	2.78 ± 0.00	2.78 ± 0.06	0.30 ± 0.03	0.30 ± 0.03	0.10 ± 0.02	0.10 ± 0.02	2.5 ± 0.2	2.5 ± 0.3	1.12 ± 0.10	1.11 ± 0.11	0.43 ± 0.02	0.43 ± 0.02
3.06	23	3.06 ± 0.00	3.08 ± 0.11	0.27 ± 0.03	0.27 ± 0.02	0.11 ± 0.01	0.10 ± 0.02	2.7 ± 0.3	2.7 ± 0.3	1.16 ± 0.11	1.16 ± 0.11	0.41 ± 0.01	0.42 ± 0.01
3.33	22	3.33 ± 0.00	3.33 ± 0.06	0.25 ± 0.02	0.25 ± 0.02	0.12 ± 0.01	0.11 ± 0.01	2.7 ± 0.2	2.8 ± 0.2	1.22 ± 0.08	1.17 ± 0.08	0.40 ± 0.01	0.41 ± 0.01
3,61	18	3.61 ± 0.00	3.64 ± 0.11	0.24 ± 0.02	0.24 ± 0.02	0.13 ± 0.01	0.12 ± 0.01	2.7 ± 0.1	2.8 ± 0.1	1.32 ± 0.06	1.28 ± 0.06	0.39 ± 0.01	0.40 ± 0.01
3.89	13	3.89 ± 0.00	3.86 ± 0.22	0.23 ± 0.02	0.23 ± 0.02	0.13 ± 0.01	0.12 ± 0.01	2.8 ± 0.2	2.8 ± 0.2	1.41 ± 0.09	1.34 ± 0.10	0.39 ± 0.01	0.39 ± 0.01
4.17	6	4.17 ± 0.00	4.11 ± 0.03*	0.22 ± 0.03	0.22 ± 0.03	0.13 ± 0.01	0.13 ± 0.01	2.8 ± 0.2	2.9 ± 0.2	1.49 ± 0.11	1.45 ± 0.12	0.38 ± 0.01	0.39 ± 0.01

Table 1: Kinematic parameters (mean ± SD) from 1.67 to 4.17 m·s^{-1} (6-15 km·h^{-1}) of target speed. MT, motorised treadmill; CNMT, curved non-motorised treadmill; n°, number of subjects; CT, contact time; FT, flight time; SF, step frequency; SL, step length; DF, duty factor. (*) significant difference ($P < 0.05$) between MT and CNMT.

Table

Table 2. Metabolic responses during the incremental test

Target Speed		Real Speed m•s^{-1}		Net $\dot{V}O_2$ mL•min^{-1}		$\dot{V}_E$ L•min^{-1}		RER ---		HR bpm		RPE ---	
m•s^{-1}	n°	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT
1.67	25	1.67 ± 0.00	1.67 ± 0.06	653.4 ± 190.1	1199.0 ± 240.3	27.8 ± 5.7	39.9 ± 8.4$^{\#}$	0.88 ± 0.09	0.88 ± 0.05	112.5 ± 15.2	122.7 ± 16.4	1.32 ± 0.85	1.20 ± 0.76
1.94	25	1.94 ± 0.00	1.92 ± 0.06	1204.1 ± 337.2	1475.7 ± 279.4	37.8 ± 7.8	47.4 ± 9.3$^{\#}$	0.82 ± 0.06	0.90 ± 0.05$^{\#}$	127.4 ± 13.1	135.3 ± 15.9	2.12 ± 0.88	1.64 ± 0.90$^{\#}$
2.22	25	2.22 ± 0.00	2.25 ± 0.06*	1558.7 ± 339.8	1878.2 ± 342.2	45.8 ± 8.2	58.6 ± 10.5$^{\#}$	0.84 ± 0.05	0.92 ± 0.06$^{\#}$	141.6 ± 13.7	150.5 ± 15.2	2.62 ± 0.88	2.32 ± 0.90
2.50	25	2.50 ± 0.00	2.47 ± 0.06*	1789.7 ± 398.2	2165.1 ± 402.2	52.7 ± 9.9	70.5 ± 9.7$^{\#}$	0.87 ± 0.05	0.97 ± 0.08$^{\#}$	151.1 ± 14.1	159.9 ± 16.4	3.30 ± 0.94	3.24 ± 1.27
2.78	25	2.78 ± 0.00	2.78 ± 0.06	2004.9 ± 437.7	2362.7 ± 422.5	59.7 ± 11.7	79.7 ± 11.1$^{\#}$	0.89 ± 0.05	1.00 ± 0.08$^{\#}$	159.7 ± 13.9	167.1 ± 14.8	4.02 ± 1.04	4.50 ± 1.73
3.06	23	3.06 ± 0.00	3.08 ± 0.11	2236.1 ± 468.3	2599.2 ± 465.2	65.5 ± 11.6	89.4 ± 12.1$^{\#}$	0.91 ± 0.04	1.03 ± 0.07$^{\#}$	166.3 ± 14.3	173.2 ± 16.0	4.89 ± 1.02	5.30 ± 1.36
3.33	22	3.33 ± 0.00	3.33 ± 0.06	2453.1 ± 468.4	2796.5 ± 500.9	75.6 ± 13.5	100.9 ± 14.5$^{\#}$	0.95 ± 0.06	1.06 ± 0.07$^{\#}$	172.3 ± 13.5	178.0 ± 11.5	5.80 ± 1.33	6.64 ± 1.81$^{\#}$
3,61	18	3.61 ± 0.00	3.64 ± 0.11	2721.1 ± 508.5	3043.4 ± 532.4	86.9 ± 16.5	114.2 ± 17.6$^{\#}$	0.98 ± 0.05	1.10 ± 0.06$^{\#}$	176.6 ± 11.9	180.8 ± 12.3	6.50 ± 1.38	7.89 ± 1.78$^{\#}$
3.89	13	3.89 ± 0.00	3.86 ± 0.22	2986.3 ± 614.8	3267.0 ± 615.4	93.4 ± 18.4	125.2 ± 20.4$^{\#}$	1.00 ± 0.06	1.14 ± 0.07$^{\#}$	179.8 ± 10.6	181.3 ± 13.8	7.58 ± 1.35	8.69 ± 1.80$^{\#}$
4.17	6	4.17 ± 0.00	4.11 ± 0.03*	111.6 ± 23.8	3780.9 ± 210.3	111.6 ± 23.8	144.0 ± 12.9$^{\#}$	1.02 ± 0.08	1.14 ± 0.06$^{\#}$	181.5 ± 8.2	185.0 ± 7.30	8.00 ± 1.41	8.67 ± 1.97

Table 2: Metabolic parameters (mean ± SD) from 1.67 to 4.17 m·s^{-1} (6-15 km·h^{-1}) of target speed. MT, motorised treadmill; CNMT, curved non-motorised treadmill; n°, number of subjects; Net $\dot{V}O_2$, net oxygen uptake; $\dot{V}_E$, pulmonary ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE rates of perceived exertion. (*) significant difference ($P < 0.05$) between MT and CNMT. (#) significant difference ($P < 0.001$) between MT and CNMT.

Table

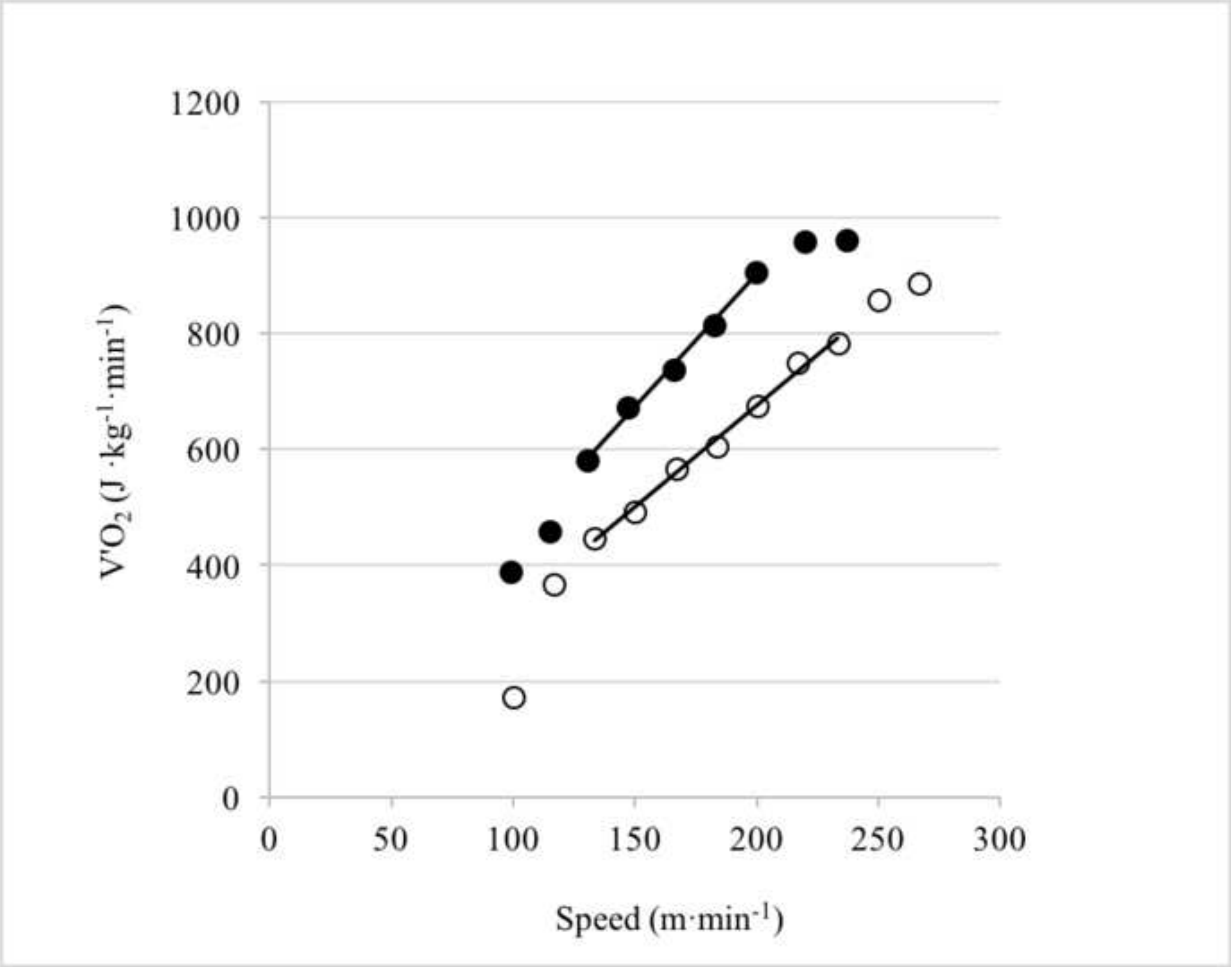
Table 3. Kinematic and metabolic data at the preferred walking speed (PWS), at maximal running speed (max) and at the gas exchange threshold (GET)

		Speed m•s^{-1}		CT s		FT s		SF steps•s^{-1}		SL m		DF ---	
	n°	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT
PWS	25	1.44 ± 0.06	1.44 ± 0.06	0.65 ± 0.07	0.66 ± 0.07	0.39 ± 0.03	0.39 ± 0.04	0.96 ± 0.20	0.95 ± 0.20*	0.75 ± 0.09	0.76 ± 0.09*	0.63 ± 0.02	0.63 ± 0.02
max	25	4.31 ± 0.50	3,75 ± 0.39$^{\#}$	0.24 ± 0.03	0.24 ± 0.02	0.12 ± 0.02	0.11 ± 0.02*	2.78 ± 0.26	2.86 ± 0.27*	1.55 ± 0.18	1.31 ± 0.16*	0.40 ± 0.02	0.40 ± 0.02

		Speed m•s^{-1}		$\dot{V}O_2$ mL•kg^{-1}•min^{-1}		$\dot{V}_E$ L•min^{-1}		RER ---		HR bpm		RPE ---	
	n°	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT	MT	CNMT
PWS	25	1.44 ± 0.06	1.44 ± 0.06	16.58 ± 2.88	22.48 ± 3.96$^{\$}$	26.4 ± 5.9	36.3 ± 8.4$^{\$}$	0.82 ± 0.05	0.87 ± 0.05$^{\$}$	104.0 ± 12.3	115.6 ± 15.1$^{\$}$	1.00 ± 0.71	1.08 ± 0.70
max	25	4.31 ± 0.50	3,75 ± 0.39$^{\#}$	49.5 ± 5.5	49.21 ± 4.82	112.5 ± 25.8	119.3 ± 22.8	1.11 ± 0.06	1.16 ± 0.06$^{\#}$	188.1 ± 11.6	184.6 ± 12.6	9.32 ± 0.99	9.36 ± 0.81
GET	25	3.56 ± 0.42	3.14 ± 0.33$^{\#}$	44.6 ± 4.8	45.98 ± 4.40	58.6 ± 31.0	73.5 ± 36.0*	1.00 ± 0.10	1.04 ± 0.10$^{\#}$	177.0 ± 9.4	174.6 ± 14.0	6.80 ± 1.00	5.84 ± 1.30$^{\$}$

Table 3: Kinematic and metabolic parameters (mean ± SD) at the preferred walking speed (PWS), at maximal running speed (max) and at the gas exchange threshold (GET). MT, motorised treadmill; CNMT, curved non-motorised treadmill; n°, number of subjects; CT, contact time; FT, flight time; SF, step frequency; SL, step length; DF, duty factor. $\dot{V}O_2$, gross oxygen consumption; $\dot{V}_E$, pulmonary ventilation; RER, respiratory exchange ratio; HR, heart rate; RPE, rate of perceived exertion. (*) significant difference ($P < 0.05$) between MT and CNMT. ($) significant difference ($P < 0.01$) between MT and CNMT. (#) significant difference ($P < 0.001$) between MT and CNMT.

Figure 1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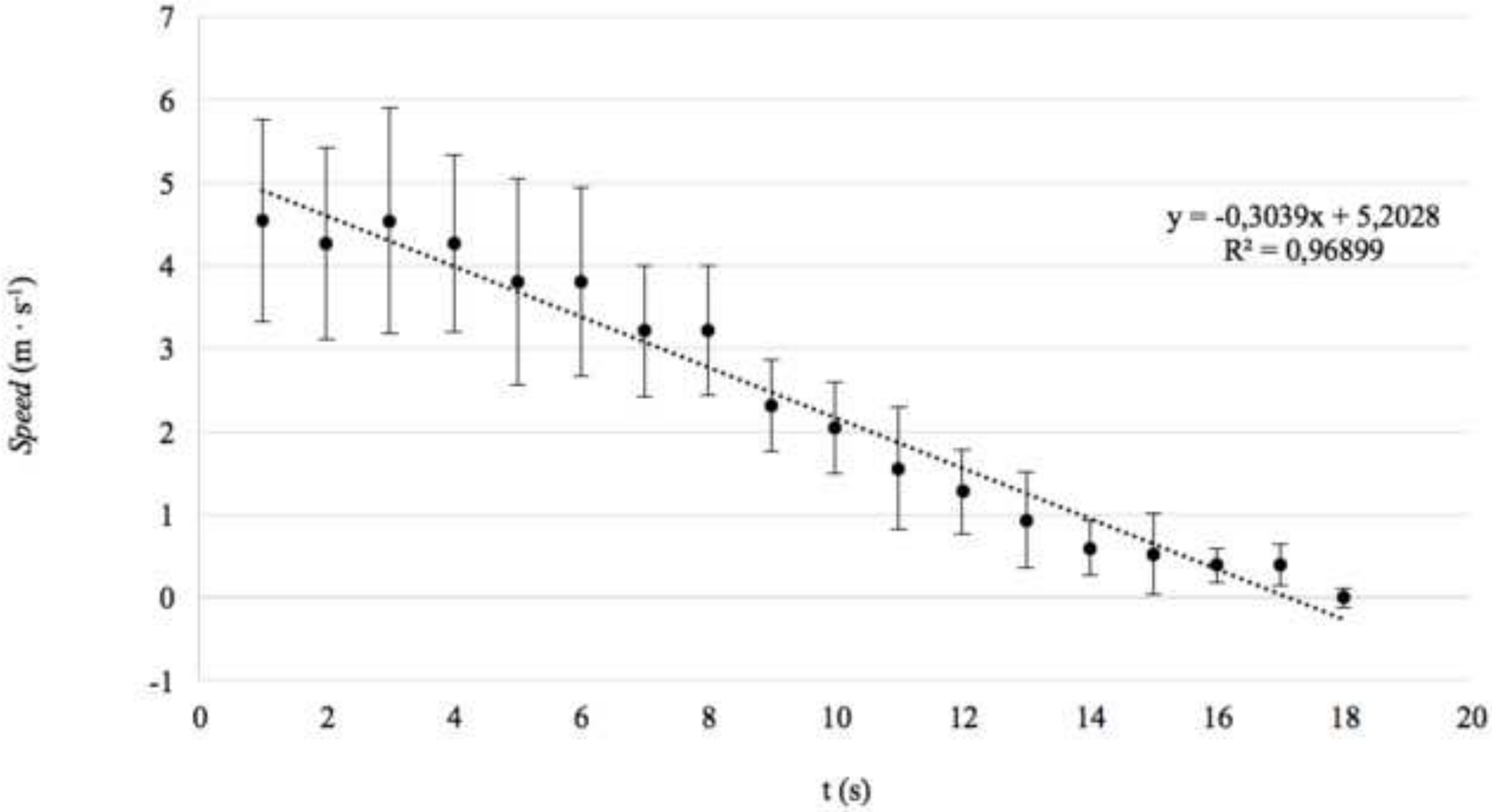
$V'O_2$ (J ·kg^{-1}·min^{-1})
Speed (m·min^{-1})

Figure 2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R² = 0,96899
Speed (m · s-1)
7
6
5
4
3
2
1
0
-1
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t (s)

Figure 3

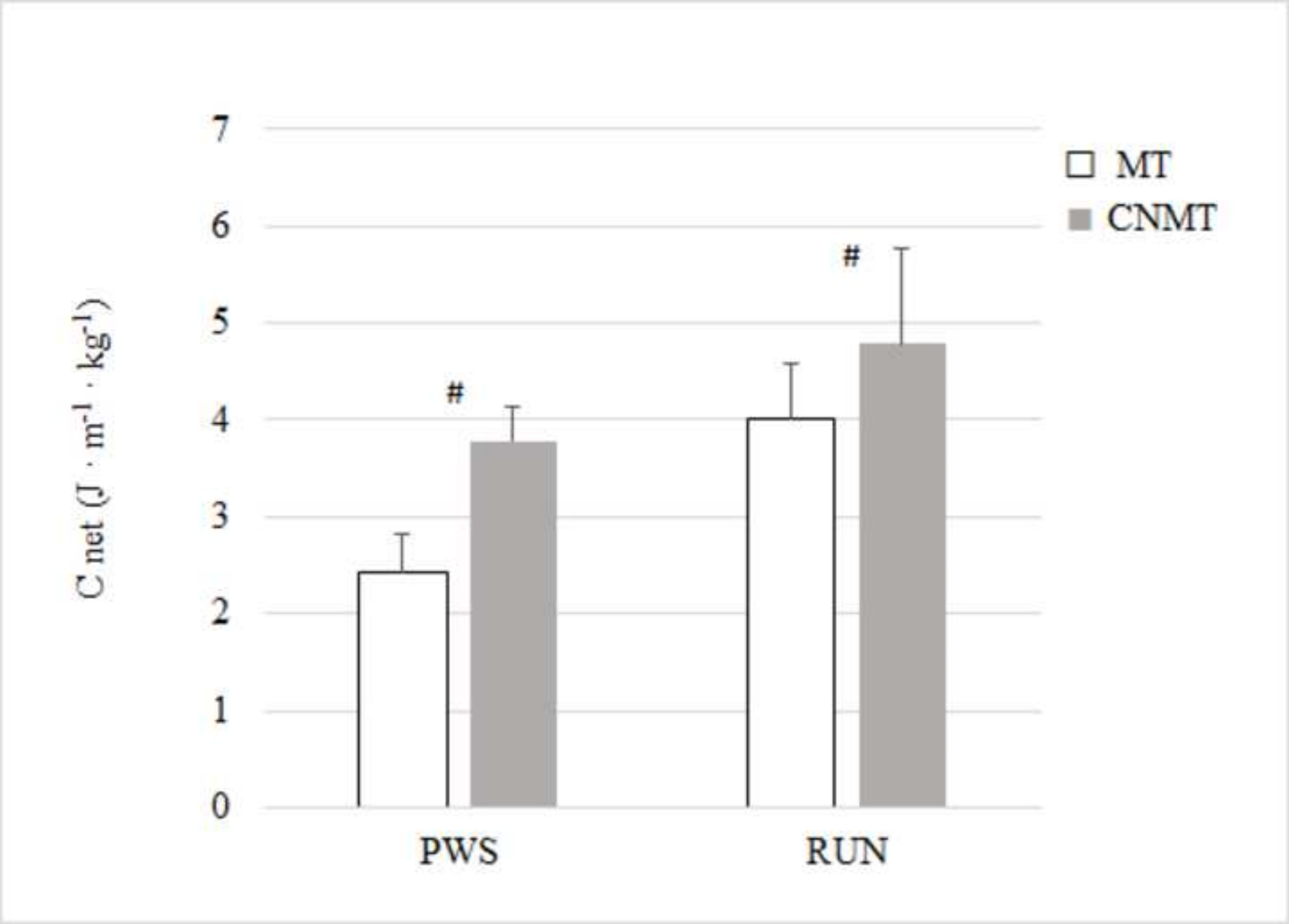
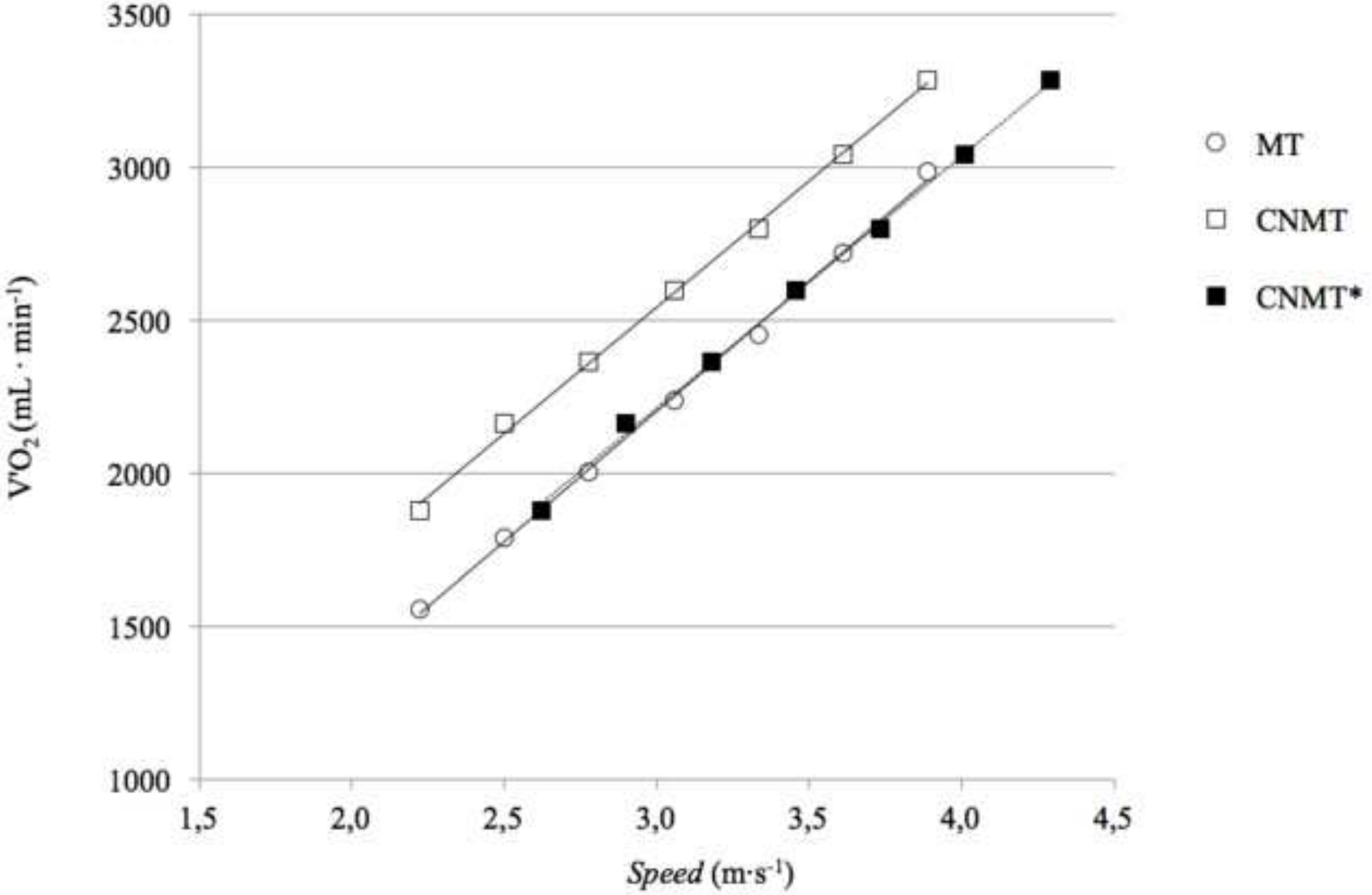


Figure 4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3000
2500
2000
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V'O$_2$ (mL · min^{-1})
1,5
2,0
2,5
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Speed (m·s^{-1})
○ MT
□ CNMT
■ CNMT*