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A 1% treadmill grade most accurately reflects the energetic cost of outdoor running

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When running indoors on a treadmill, the lack of air resistance results in a lower energy cost compared with running outdoors at the same velocity. A slight incline of the treadmill gradient can be used to increase the energy cost in compensation. The aim of this study was to determine the treadmill gradient that most accurately reflects the energy cost of outdoor running. Nine trained male runners, thoroughly habituated to treadmill running, ran for 6 min at six different velocities (2.92, 3.33, 3.75, 4.17, 4.58 and 5.0 m s^{-1}) with 6 min recovery between runs. This routine was repeated six times, five times on a treadmill set at different grades (0%, 0%, 1%, 2%, 3%) and once outdoors along a level road. Duplicate collections of expired air were taken during the final 2 min of each run to determine oxygen consumption. The repeatability of the methodology was confirmed by high correlations (r = 0.99) and non-significant differences between the duplicate expired air collections and between the repeated runs at 0% grade. The relationship between oxygen uptake ($\dot{V}O_2$) and velocity for each grade was highly linear (r > 0.99). At the two lowest velocities, $\dot{V}O_2$ during road running was not significantly different from treadmill running at 0% or 1% grade, but was significantly less than 2% and 3% grade. For 3.75 m s^{-1}, the $\dot{V}O_2$ during road running was significantly different from treadmill running at 0%, 2% and 3% grades but not from 1% grade. For 4.17 and 4.58 m s^{-1}, the $\dot{V}O_2$ during road running was not significantly different from that at 1% or 2% grade but was significantly greater than 0% grade and significantly less than 3% grade. At 5.0 m s^{-1}, the $\dot{V}O_2$ for road running fell between the $\dot{V}O_2$ value for 1% and 2% grade treadmill running but was not significantly different from any of the treadmill grade conditions. This study demonstrates equality of the energetic cost of treadmill and outdoor running with the use of a 1% treadmill grade over a duration of ~5 min and at velocities between 2.92 and 5.0 m s^{-1}.

Keywords: Fitness assessment, running economy, treadmill running.

Introduction

In recent years there has been a growing interest by athletes and coaches in physiological tests which track changes in training status, predict current performance capability and which may help guide prescription of training programmes. This has focused attention on the validity of transferring information gained in the laboratory to the outdoor environment. For runners and team-game players, the motorized treadmill is commonly used to impose an exercise stress; however, unlike outdoor running, there is no air resistance during treadmill running. This has potential consequences for both thermoregulation and the energy cost of overcoming air resistance. The movement of air over the body aids convective heat loss and can reduce exercise heart rate, since the demand for peripheral blood flow is reduced (Riggs *et al.*, 1981; Williams and Kilgour, 1993). To compensate for this, electric fans are commonly used in the laboratory. Moving air from a fan aids convective heat loss but the mass of moving air is far too small to impose any significant force retarding forward motion. In order to compensate for the lack of air resistance, some researchers have used slight inclinations of the treadmill, including 1.0% (Heck *et al.*, 1985) and 2.0% (Tegtbur *et al.*, 1993); however neither of these studies reported data in support of

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their chosen adjustment. Other researchers have not made any attempt to account for the effect of air resistance (Noakes *et al.*, 1990; Weltman *et al.*, 1990) or else made no reference to the matter (Hale *et al.*, 1988).

The aim of this study was to determine the treadmill gradient that most accurately reflects the energy cost of outdoor running over the range of velocities commonly used for training and racing in a group of good standard runners. We hypothesized that oxygen uptake ($\dot{V}O_2$) when running on the level outdoors would be higher at any given velocity than $\dot{V}O_2$ when running on a level treadmill indoors and that the difference would increase with increasing velocity.

Methods

Subjects and experimental plans

Nine male runners who were in regular training for distance running, and who were thoroughly familiar with treadmill ergometry and laboratory procedures, volunteered to participate in the study. The subjects provided written informed consent and the experimental protocol was approved by the local ethical committee. The subjects' mean (– S.D.) age, body mass, sum of four skinfolds (Durnin and Womersley, 1974) and $\dot{V}O_2$ max were 24.9 –5.2 years, 72.0 –3.3 kg, 24.9 –5.7 mm and 65.1 –2.7 ml kg $^{-1}$ min^{-1}, respectively.

The subjects were required to run for 6 min at each of six different velocities (2.92, 3.33, 3.75, 4.17, 4.58 and 5.0 m s^{-1}, i.e. 10.5-18.0 km h^{-1}) with 6 min recovery between runs. This routine was repeated six times, five times on a treadmill set at different grades (0%, 0%, 1%, 2%, 3%) and once outdoors. The 0% treadmill grade condition was applied twice to allow assessment of the reliability of the test methodology. The tests took place on six separate days and the six conditions were applied in random order. Testing was completed within 2 weeks for all subjects. The velocities were selected to represent typical training and competition velocities for competitive but non-elite male runners.

On each occasion, the subjects reported to the laboratory following an overnight fast and each subject was tested at the same time of day (06.00-08.30 h). Strenuous training was forbidden in the 24 h preceding each test. The subjects wore the same footwear and lightweight running kit on each occasion, and performed the same individual warm-up routine.

During the last 2 min of each run, $\dot{V}O_2$ was determined by indirect calorimetry. The subjects breathed through a Salford low-resistance valve and wide-bore Falconia tubing. Expired air was collected into Douglas bags over a period of 50 s. Duplicate collections were made to assess the repeatability of the method and also to establish whether a steady-state had been reached. Expired air was analysed for the concentrations of O_2 and CO_2 through a paramagnetic transducer (Servomex series 1100, Crowborough, England) or an infrared transducer (Servomex model 1490) respectively, previously calibrated using three-point standards. Gas volume was determined using a dry gas meter (Harvard Ltd, Edenbridge, England), previously calibrated using a Tissot spirometer and checked against a precision 7 litre gas syringe (Hans Rudolph Inc., Kansas, USA). All gas volumes were corrected to standard temperature and dry pressure. Heart rate (HR) was measured telemetrically using a Polar Sport Tester heart rate monitor (Polar Electro, Kempele, Finland).

Treadmill procedures

The subjects ran on a slatted-belt Woodway model ELG2 treadmill (CardioKinetics, Salford, England). The treadmill speed was checked by timing belt revolutions during the last minute of each run for each subject. The treadmill speed was always within 0.03 m s^{-1} of the desired speed. The treadmill gradient was checked by a spirit level and large protractor arranged on a long flat plank of wood. Through a screwthread device, the spirit level could be adjusted to the exact horizontal and the grade read from the protractor.

Outdoor procedures

For the outdoor condition, the subjects ran on a level (0.2 m descent in 1.6 km) seafront promenade using an out-and-back course. They were paced at the appropriate velocities by an experimenter who cycled at a steady pace 2 m to the side of the subject. The cycle was fitted with a 'bicycle computer' for continuous monitoring of velocity and distance covered. The bicycle computer was calibrated regularly using the treadmill to ensure consistency in velocity measurements between the indoor and outdoor conditions. The total time taken to cover the distance gave an independent confirmation of the average velocity of running. Actual velocities for each individual were used in the data analysis and these were within –0.06 m s $^{-1}$ of the desired velocity. Shortly after reaching the designated turning point for each run, the subjects were fitted with a nose clip and mouthpiece. After 60 s to allow habituation, $\dot{V}O_2$ was determined by the same method used in the treadmill runs. The Douglas bag was supported by another experimenter running about 1 m to the side and slightly behind the subject. This method ensured minimal interference to the air movement experienced by the subject. Wind speed was continually monitored using an anemometer. Outdoor running was only performed if the wind speed was less than 2.0 m s^{-1};

Table 1 Mean (– S.D.) oxygen consumption (ml kg^{-1} min^{-1}) at each velocity (m s^{-1}) and in each experimental condition

Running velocity	Experimental condition				
	0% grade	1% grade	2% grade	3% grade	Level road
2.92	29.6 –1.2 [c,d]	31.3 –1.4 [c,d]	33.2 –1.7 [a,b,d]	35.6 –1.6 [a,b,c,e]	31.1 –1.8 [c,d]
3.33	34.6 –1.9 [c,d]	36.4 –1.6 [c,d]	38.4 –1.7 [a,b,d,e]	40.9 –1.3 [a,b,c,e]	35.7 –1.3 [c,d]
3.75	39.0 –1.9 [b,c,d,e]	41.4 –1.2 [a,c,d]	44.1 –1.9 [a,b,d,e]	46.5 –1.7 [a,b,c,e]	41.7 –1.3 [a,c,d]
4.17	44.9 –1.9 [b,c,d,e]	48.3 –1.5 [a,d]	50.3 –2.4 [a,d]	53.0 –1.7 [a,b,c,e]	48.1 –2.2 [a,d]
4.58	51.0 –2.0 [c,d,e]	55.3 –2.3 [a,d]	56.9 –2.3 [a]	59.3 –2.3 [a,b,e]	54.8 –2.7 [a,d]
5.00	57.3 –2.7 [c,d]	58.1 –2.6 [d]	61.9 –2.6 [a]	64.2 –2.7 [a,b]	60.5 –3.0

Significantly different ($P < 0.05$) from: [a]0% grade, [b]1% grade, [c]2% grade, [d]3% grade, [e]level road.

usually wind speed was much less than this and averaged 0.2 –0.5 m s^{-1}. The laboratory and outside temperatures were similar and ranged between 14¡ and 18¡ C.

Statistical analyses

Repeatability data were analysed with Pearson product-moment correlation coefficients and paired *t*-tests. The $\dot{V}O_2$ and HR at different running velocities and grades were analysed with analysis of variance with the site of significant ($P < 0.05$) differences determined using Tukey's *post-hoc* comparison.

Results

Attainment of a steady-state

It is of major importance to this study that measurements were made in the steady-state and were reliable. The $\dot{V}O_2$ was measured twice during the last 2 min of each run. The two collections were highly correlated ($r = 0.99$). For all collections (over all velocities and grades both indoors and outdoors), the $\dot{V}O_2$ from the first Douglas bag (43.8 –10.3 ml kg^{-1} min^{-1}) was not significantly different to the $\dot{V}O_2$ from the second Douglas bag (44.0 –10.5 ml kg^{-1} min^{-1}). The mean of the two collections was used in the data analysis. Test-retest reliability was assessed at 0% grade. The data were highly correlated ($r = 0.99$) and were not significantly different between the two tests. Heart rate during test 2 was lower than HR during test 1 and this approached significance ($P = 0.053$). However, the mean difference in HR between test and retest (1.6 beats min^{-1}) was trivially small.

Oxygen consumption

Table 1 shows the oxygen consumption at each velocity for each condition. The $\dot{V}O_2$ during road running was not significantly different from that at 1% treadmill grade at any velocity. The trend was for road running to require a similar oxygen cost to 0% or 1% grade at the slower velocities, while at higher velocities the oxygen cost of road running was closer to the oxygen cost of treadmill running at 1% and 2% grade. At 5.0 m s^{-1}, the $\dot{V}O_2$ during road running was not significantly different from the $\dot{V}O_2$ at any treadmill grade.

The relationship between $\dot{V}O_2$ and running velocity (v) was highly linear. Regression equations for the various treadmill grades and for road running were as follows ($\dot{V}O_2$ in ml kg^{-1} min^{-1}; v in m s^{-1}):

0%	$\dot{V}O_2 = 13.7v - 11.10$	($r = 0.99$, S.E. $= 0.46$)
1%	$\dot{V}O_2 = 13.5v - 8.50$	($r = 0.99$, S.E. $= 1.12$)
2%	$\dot{V}O_2 = 14.1v - 8.23$	($r = 0.99$, S.E. $= 0.47$)
3%	$\dot{V}O_2 = 14.0v - 5.64$	($r = 0.99$, S.E. $= 0.48$)
Road	$\dot{V}O_2 = 14.4v - 11.90$	($r = 0.99$, S.E. $= 0.65$)

Figure 1 shows the relationship between $\dot{V}O_2$ and velocity for each condition with the regression lines shown. Heart rate followed a similar pattern of change to that shown by oxygen uptake (Table 2). Running on a level road elicited a heart rate ~3-4 beats min^{-1} higher than that found during running on a flat treadmill.

Discussion

The results demonstrate the oxygen cost of running on the level outdoors is greater than when running on the level indoors. A 1% treadmill grade was found to reflect most accurately the oxygen cost of running outdoors and the oxygen cost at this grade was not significantly different to the oxygen cost of outdoor running for velocities between 2.92 and 5.0 m s^{-1}. These results confirm the finding of Davies (1980), who, using data obtained from a limited number of subjects running on a treadmill housed in a wind tunnel, reasoned that the

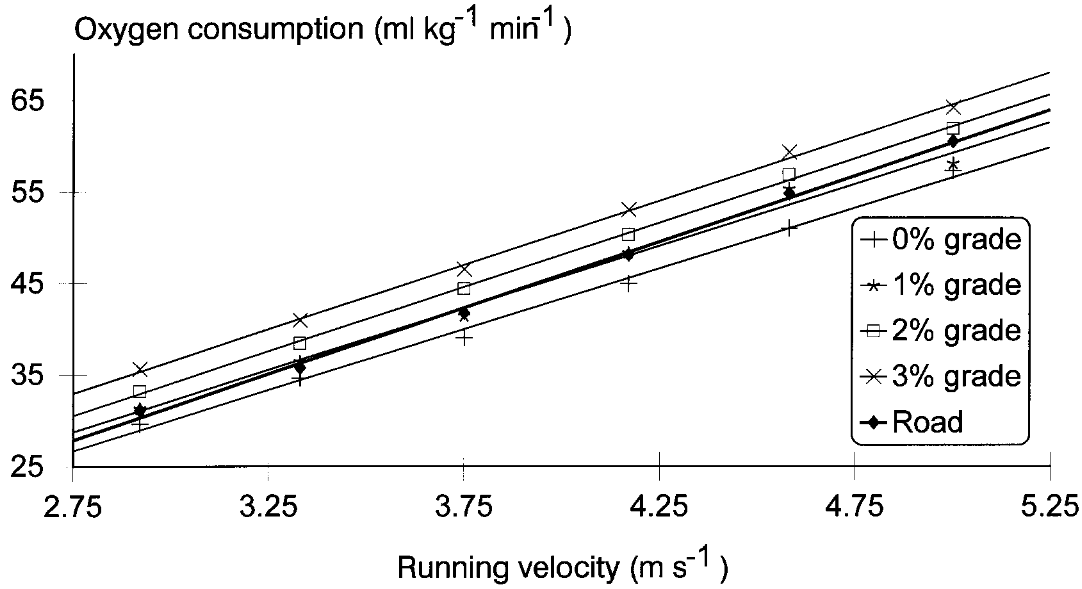

Figure 1 The relationship between oxygen consumption and running velocity on the road and at various treadmill grades.

air resistance experienced during outdoor running on a calm day was equivalent to running on a treadmill with 1% slope. The present data also reinforce the work of Heck *et al.* (1985), who measured blood lactate but not $\dot{V}O_2$ at a variety of treadmill grades (0%-6%) and during outdoor running on a variety of surfaces. They concluded that a treadmill gradient set somewhere between 0% and 2% was necessary to allow application of laboratory data to field conditions.

Accurate evaluation of the energy demand for particular running velocities requires that exercise is performed in the steady-state. Barstow and Mole (1991) showed that for intensities below the lactate threshold, a steady-state for $\dot{V}O_2$ is attained in less than 3 min, while for moderate-intensity work above the lactate threshold the attainment of a steady-state is delayed. A $\dot{V}O_2$ steady-state may never be attained during constant load exercise at intensities greater than about 90% $\dot{V}O_2$ max (Barstow and Mole, 1991). For the subjects in the present experiment, lactate threshold (measured in a parallel study by Jones and Doust, 1995) occurred at between 4.58 and 5.14 m s^{-1}, so some of the subjects would have been exercising above the lactate threshold for the 5 m s^{-1} condition. However, despite the probability of elevated blood lactate levels in some subjects at 5.0 m s^{-1}, the duplicate $\dot{V}O_2$ determinations were not significantly different and all subjects were able to complete the 6 min of running. For a minority of subjects at 5 m s^{-1} and at the higher grades of 2% and 3%, oxygen uptake approached $\dot{V}O_2$ max. This led to a larger standard error of the mean $\dot{V}O_2$ and is the probable explanation for the insignificant differences between conditions found at 5 m s^{-1}.

While the $\dot{V}O_2$-velocity relationship for outdoor running is theoretically curvilinear, with $\dot{V}O_2$ increasing as

Table 2 Mean (– s.d.) heart rate (beats min^{-1}) at each velocity (m s^{-1}) and in each experimental condition

Running velocity	Experimental condition: 0% grade	1% grade	2% grade	3% grade	Level road
2.92	116 –7 ^{c,d}	119 –8 ^{c,d}	126 –7 ^{a,b,e}	132 –6 ^{a,b,e}	119 –6 ^{c,d}
3.33	124 –6 ^{c,d}	128 –7 ^{d}	134 –7 ^{a}	141 –6 ^{a,b,e}	128 –7 ^{d}
3.75	137 –6 ^{c,d}	140 –6 ^{d}	143 –6	153 –7 ^{a,b,e}	140 –8 ^{d}
4.17	149 –6 ^{c,d}	153 –7 ^{d}	155 –7	164 –7 ^{a,b,e}	153 –7 ^{d}
4.58	160 –7 ^{c,d}	164 –7 ^{d}	166 –9	174 –9 ^{a,b}	165 –7
5.00	171 –9 ^{c,d}	173 –8 ^{d}	175 –9	186 –11 ^{a,b}	174 –9

Significantly different ($P < 0.05$) from: ^{a}0% grade, ^{b}1% grade, ^{c}2% grade, ^{d}3% grade, ^{e}level road.

a cubic function of velocity (Pugh, 1970, 1971), Leger and Mercier (1984) reported that, at least for velocities below 6.94 m s^{-1}, the relationship can be adequately described by a linear function. Interestingly, however, their regression equation for outdoor running was distinctly different from that used to describe level grade treadmill running, particularly for velocities exceeding 4.17 m s^{-1}. Despite the non-linearity between $\dot{V}O_2$ and velocity described by Pugh (1970) for track running, Pugh also noted that the relationship could be adequately described by a linear function between 2.22 and 6.11 m s^{-1}, an observation subsequently confirmed by McMiken and Daniels (1976) and Davies (1981). In the present study, a linear equation was found to fit the $\dot{V}O_2$-velocity relationship almost perfectly (r^2 = 99.7%), whereas a square function and a cubic function fitted less well (r^2 = 98.3% and 95.7%, respectively). Extrapolation of the data to velocities in excess of 5.0 m s^{-1} should be made with caution since, from both physical principles and empirical studies during human locomotion, the $\dot{V}O_2$-velocity relationship takes on greater curvilinearity at higher velocities (McMiken and Daniels, 1976; Davies, 1980). Nevertheless, the trend of the data, with the slope of the regression for the road condition tending to be greater than that of any of the other regressions (see Fig. 1), suggest that at running velocities of ~5-6 m s^{-1}, a grade of 2% might best reflect the $\dot{V}O_2$ of horizontal outdoor running, while at velocities around 2-3 m s^{-1}, a grade of 0.5% is most appropriate. Although the subjects in this study were trained males, there is no evidence to suggest that the $\dot{V}O_2$-velocity relationship differs between males and females (Falls and Humphreys, 1976; Daniels *et al.* 1986; Daniels and Daniels, 1992).

The regression equation for $\dot{V}O_2$ on velocity during horizontal treadmill running in the present study was similar to other data on trained runners (Costill *et al.*, 1973; McMiken and Daniels, 1976; Bransford and Howley, 1977). However, $\dot{V}O_2$ at any velocity was consistently lower (i.e. the running economy was greater) than has been reported previously for untrained subjects (Shephard, 1969; Bransford and Howley, 1977; Bassat *et al.*, 1985; ACSM, 1991), and the regression equation for the present study provided $\dot{V}O_2$ estimates that were considerably lower than those provided by the general equation calculated by Leger and Mercier (1984) from pooled data of numerous early studies. Evidence for better running economy in trained subjects is compelling (Daniels and Daniels, 1992; Morgan and Craib, 1992; Morgan *et al.*, 1994). However, even in the present subjects, with high and relatively homogeneous $\dot{V}O_2$ max scores (coefficient of variation = 4%), large inter-individual differences in running economy were observed. For example, the $\dot{V}O_2$ measured at 4.58 m s^{-1} and 1% grade ranged from 49.3 to 57.0 ml kg^{-1} min^{-1}. These results underline the potential error in the prediction of $\dot{V}O_2$ max from performance tests such as the multi-stage shuttle (Ramsbottom *et al.*, 1988), and in performance prediction from $\dot{V}O_2$ max alone in groups with relatively similar $\dot{V}O_2$ max scores (Morgan *et al.*, 1989). Other investigators have reported wide inter-individual differences in running economy in groups of runners with homogeneous $\dot{V}O_2$ max and have shown that running economy can discriminate performance in such groups (Conley and Krahenbuhl, 1980; Powers *et al.*, 1983).

Other potential causes for differences between treadmill and outdoor running include the runner gaining some energy from the motor-driven treadmill belt, changes in the pattern of locomotion due to differing surfaces or to instability consequent on visual cues arriving from static rather than moving surroundings (Van Ingen Schenau, 1980), and the degree of habituation to treadmill running (Conley and Krahenbuhl, 1980). Van Ingen Schenau (1980) has questioned whether there is any fundamental difference between the two types of running. He demonstrated mathematically that as long as the treadmill belt velocity is constant, then mechanically it is appropriate to use a coordinate system that moves with the belt. With such a system, no mechanical difference exists between treadmill and overground running. Although in some treadmills the belt speed can be unstable, the modern high-velocity machines designed for precision scientific work not only provide stable control of speed but also a slatted surface that gives the runner very similar proprioceptive feedback to running overground. It is possible that some of the difference in $\dot{V}O_2$ measured between treadmill and outdoor running was a consequence of the different elastic properties of the two contact surfaces. Since the subjects wore the same running shoes on each occasion, 50% of the effect of surface interactions was removed. The coefficient of restitution (e) of the treadmill and the road was determined using a basketball (to most closely reflect the characteristics of running shoe rubber and in-sole air bags). The ball-treadmill (e = 0.62) and ball-road (e = 0.64) interactions were similar and suggest the results of our study were not affected by differences in the elastic properties of the surfaces. For athletes who are fully habituated to treadmill running, as in the present study, any effect on energy costs is likely therefore to be associated with the effects of air resistance. That our data showed an effect proportional to running velocity supports our view that the causal factor for the difference between indoor and outdoor running is the extra work required to move through the air rather than the result of mechanical factors.

In conclusion, this study is the first to demonstrate no significant difference between the $\dot{V}O_2$ measured at velocities between 2.92 and 5.0 m s^{-1} during outdoor running and the $\dot{V}O_2$ measured at the same velocity during indoor treadmill running at 1% grade over a period of around 5 min. This indicates that accurate extrapolation of data generated by physiological assessment of trained runners to conditions of outdoor road running requires that the treadmill be set at a grade of 1%. The difference in the oxygen cost between outdoor running and treadmill running at 0% grade is relatively small, rising from ~1.5 ml kg^{-1} min^{-1} at 2.92 m s^{-1} to ~3 ml kg^{-1} min^{-1} at 5.0 m s^{-1}. However, this difference equates to a difference between treadmill and outdoor running velocity of about 0.07 m s^{-1} at the slowest velocity, rising to about 0.28 m s^{-1} at the highest velocity. Expressed in terms of heart rate, the difference is up to 8 beats min^{-1}. Such differences are of meaningful magnitude in the prescription of athletic training programmes. The use of appropriate treadmill grades to compensate for the lack of air resistance in the laboratory setting will help to improve the precision with which applications to outdoor training and competition can be made.

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