Is there an optimum speed for economical running?

Original Investigation

Matthew I. Black[1], **Joseph C. Handsaker**[1,2], **Sam J. Allen**[1], **Stephanie E. Forrester**[3], **and Jonathan P. Folland**[1]

[1]School of Sport, Exercise and Health Sciences, Loughborough University, Leicestershire, LE11 3TU, England, UK.

[2]MAS Innovation, Colombo, Sri Lanka

[3]Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, England, UK.

Address for Correspondence:
Matthew I. Black
School of Sport, Exercise and Health Sciences, Loughborough University, Leicestershire,
LE11 3TU, United Kingdom.
Tel: +44 (0)1509 226440
E-mail: M.I.Black@lboro.ac.uk

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Abstract

The influence of running speed and sex on running economy is unclear and may have been confounded by measurements of oxygen cost that do not account for known differences in substrate metabolism, across a limited range of speeds, and differences in performance standard. Therefore, this study assessed the energy cost of running over a wide-range of speeds in high-level and recreational runners to investigate the effect of speed (considered in absolute and relative terms) and sex (males vs. females of equivalent performance standard) on running economy. 92 healthy runners (high-level males, *n*=14; high-level females, *n*=10; recreational males, *n*=35; recreational females, *n*=33) completed a discontinuous incremental treadmill test for the determination of the energy cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) of submaximal running, speed at lactate turnpoint (*s*LTP) and the maximal rate of oxygen uptake ($\dot{V}O_2max$). There were no sex-specific differences in the energy cost of running for the recreational or high-level runners when compared at absolute or relative running speeds ($P>0.05$). The absolute and relative speed-energy cost relationships for the high-level runners demonstrated a curvilinear inverted "u-shape" with a nadir reflecting the most economical speed at 13 $km.h^{-1}$ or 70% *s*LTP. The high-level runners were more economical than the recreational runners at all absolute and relative running speeds ($P<0.05$). These findings demonstrate that there is an optimal speed for economical running; there is no sex-specific difference; and, high-level endurance runners exhibit a better running economy than recreational endurance runners.

Key words: Running economy; energy cost; distance running; sex, speed; performance standard

Introduction

Distance running performance is dependent on the speed that can be sustained for the duration of an event. This speed is determined by the interaction of several physiological factors[1] which include: the maximal rate of oxygen uptake ($\dot{V}O_2$max); the anaerobic capacity; the fractional utilisation of $\dot{V}O_2$max; and the conversion of this energy into forward movement, known as running economy. The importance of running economy as a physiological determinant of distance running performance is well documented[1,2] and is emphasised by its ability to discriminate between performance capabilities in athletes with a similar $\dot{V}O_2$max.[3] Furthermore, distance running events appear to be dominated by highly economical athletes.[4] However, despite its importance for distance running performance[1,2], the influence of sex and running speed on running economy remains unclear, and may be confounded by differences in the performance standards of runners.

The relationship between speed and running economy is highly equivocal[5] with reports that running is more[6-7] and less[9] energetically expensive as a function of speed. These conflicting findings may be in part due to the relatively small range of speeds (e.g., ≤4 $km \cdot h^{-1}$)[6-8] and differing absolute speeds in these studies, which may have limited their ability to describe the full speed-running economy relationship. In contrast, some small reports (n=9) that examined a larger range of speeds observed a curvilinear "u-shaped" relationship between running economy and speed.[10,11] Further research is therefore necessary to investigate the relationship between running economy and speed in a large sample of runners across a large range of speeds.

Evidence for a sex-dependent difference in running economy is also unclear[5] with reports demonstrating that males[12,13] and females[14,15] are the more economical sex, or that there is no difference.[7,16] Notably, these studies involved a small sample (n≤30)[7,14,15] or were limited to comparisons across absolute speeds.[12-14,16] Differences in performance standard could explain some of the confusion with regard to the influence of sex and speed on running economy. Performance standard has not been accounted for in the majority of the previous studies of sex and speed even though it has been consistently demonstrated that higher standard runners are more economical.[17,18] It is therefore important to establish the effect of sex on running economy at the same absolute and relative speeds for runners of equivalent performance standard (e.g. high level and/or recreational).

The majority of the literature concerning running economy, quantified running economy as the oxygen cost to maintain a given speed and/or to cover a given distance based on the assumption that $\dot{V}O_2$ provides an index of the underlying energetic demands.[6] However, the energy equivalent for a given $\dot{V}O_2$ can vary according to the substrate metabolised,[19] which has been shown to be dependent on sex,[20] intensity/speed,[21] and can be altered with training[20] and thus is likely to differ according to performance standard. Therefore, the previous comparisons of running speed, sex and performance standard that used the oxygen cost of running as the measure of running economy may have been confounded by differences in substrate metabolism. The assessment of the underlying energy cost accounts for these differences in substrate metabolism and provides a more valid index for the assessment of running economy.[6,8]

Due to the methodological limitations of previous investigations a more comprehensive study that investigates the influence of speed and sex on the energy cost of running across a wide-range of speeds (absolute and relative intensities), and controls for performance standard, is clearly warranted. The purpose of the present study, therefore, was to assess the effect of speed and sex on running economy in a large sample of runners. We hypothesised that: 1) the energy cost of running would increase as a function of running speed; 2) there would be no sex-specific difference in the energy cost of running at the same absolute or relative speeds (% speed at lactate turnpoint, % *s*LTP) for runners of equivalent performance standard; and, 3) that high-level endurance runners would have a lower energy cost for running at all absolute and relative running speeds compared to recreational runners.

METHODS

Participants

Ninety-two healthy endurance runners (Table 1) volunteered and gave written informed consent to participate in this study, which had been approved by the Loughborough University Ethical Advisory Committee. All participants were regular runners (≥2x per week) who considered running to be their primary sport or physical activity and had a BMI <24 $kg \cdot m^{-2}$. Participants were free from moderate/serious musculoskeletal injury and any minor musculoskeletal injury in the 3 months, and 1 month prior to testing, respectively. Runners were recruited (Table 1) to provide male and female groups of both high-level and recreational runners according to their best running performance in the previous 12 months for distances between 1500 m and the marathon in UK Athletics sanctioned track and road races. All times were converted to an equivalent 10-km road time using IAAF points scores,[23] and are presented as a percentage of the 10-km road World Record time (Male, 26 min 44 s; Female, 30 min 21 s). The 24 high-level runners (males, *n*=14; females, *n*=10) were within 115% of the 10-km World Record Time (<31 min for males; <35 min for females), and the 68 recreational runners (males, *n*=35; females, *n*=33) had achieved between 133-202% of the 10-km World Record Time (35-54 min for males; 40-61 min for females; Table 1).

Experimental Overview

Participants visited the laboratory on two occasions separated by 2-14 days, to perform a treadmill familiarisation and experimental session. Participants were instructed to report to the laboratory in a well-hydrated, rested state, having completed no strenuous exercise within the previous 36 h, after their habitual nutrition and having abstained from alcohol and caffeine for the preceding 24 h, and 6 h respectively. The experimental visit comprised a submaximal treadmill running test, immediately followed by a maximal treadmill running test. All experimental visits were conducted in the morning (0730-1200), and laboratory conditions were similar for all participants (temperature, 18-20°C; relative humidity, 45-55%). During both visits, all participants were required to wear the same neutral racing flat shoes (New Balance® RC 1400 v2).

Familiarisation

The familiarisation started with the subject ‘straddling’ the motorised treadmill belt (HP Cosmos, Venus T200, Nussdorf-Traunstein, Germany), such that the treadmill belt could revolve without requiring the participant to run. The participants then practiced lowering themselves onto, and lifting themselves clear of the moving treadmill belt a minimum of three times at each speed, increasing in 1 km.h^{-1} increments from 7 km.h^{-1} until the participant indicated that they could not continue. Following a period of rest (~5 min), the subject was fitted in a low-dead space mask and breathed through an impeller turbine assembly (Jaeger Triple V, Jaeger GmbH, Hoechberg, Germany), and repeated the treadmill familiarisation. Following the familiarisation session, the subjects were capable of safely lowering themselves onto the moving treadmill belt and running freely in approximately 3-s.

Experimental visit

Submaximal and maximal running assessment

Participants performed a discontinuous submaximal incremental test for the determination of the energy cost of running, *s*LTP and $\dot{V}O_2$max. The test started at 7 km.h^{-1} for females, and 8 km.h^{-1} for males and consisted of 4 min stages of running at each speed, in increments of 1 km·h^{-1}, interspersed by 30-s rest periods during which the subject straddled the moving treadmill belt for fingertip capillary blood sampling. Increments were continued until blood lactate (BLa) had risen >2 mmol·L^{-1} from the previous stage (or exceeded 4 mmol·L^{-1}), at which point, the participant started the maximal running assessment, and the treadmill speed was increased by 1 km·h^{-1} every 2 min until volitional exhaustion. Pulmonary gas exchange was recorded throughout.

Measurements

Anthropometry

During the experimental visit, prior to exercise, body mass was measured using digital scales (Seca 700; Seca Hamburg, Germany) to the nearest 0.1 kg, and height was recorded to the nearest 1 cm using a stadiometer (Harpenden Stadiometer, Holtain Limited, UK).

Capillary blood analysis

A ~30-µL capillary blood sample was taken from the fingertip for analysis of BLa (YSI 2300, Yellow Springs Instruments, Yellow Springs, OH) following the completion of each submaximal running speed. The LTP was identified via a derivation of the modified Dmax method[24]. Briefly, a fourth order polynomial curve was fitted to the speed-lactate relationship. Lactate threshold (LT) was identified as the final stage preceding an increase in BLa >0.4 mmol·L^{-1} above baseline and a straight line was drawn between LT and the last 4-min stage of running (i.e., an increase >2 mmol·L^{-1} or exceeding 4 mmol·L^{-1}). Finally, LTP was defined as the greatest perpendicular distance between this straight line and the fourth order polynomial, to the nearest 0.5 km·h^{-1}.

Pulmonary gas exchange

Breath-by-breath pulmonary gas exchange data were measured continuously throughout the submaximal-, and maximal- protocols. Subjects wore a low-dead space mask and breathed through an impeller turbine assembly (Jaeger Triple V, Jaeger GmbH, Hoechberg, Germany). The inspired and expired gas volume and concentration signals were continuously sampled, the latter using paramagnetic (O_2) and infrared (CO_2) analysers (Jaeger Vyntus CPX, Carefusion, San Diego, CA) via a capillary line. These analysers were calibrated before each test using a known gas mixture (16% O_2 and 5% CO_2) and ambient air. The turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, KS). The volume and concentration signals were time aligned, accounting for the transit delay in capillary gas and analyser rise time relative to the volume signal. Breath-by-breath $\dot{V}O_2$ data were initially examined to exclude errant breaths caused by coughing, swallowing etc., and those values lying more than 4 SD from the local mean were removed. Subsequently, the breath-by-breath data were converted to second-by-second data using linear interpolation. $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}_E$ and RER were quantified for the final 60-s of each stage of the submaximal protocol. $\dot{V}O_2$max was determined as the highest 30-s moving average.

Calculation of the energy cost of running

The 60-s average $\dot{V}O_2$ and $\dot{V}CO_2$ data collected during the final minute of each submaximal stage were used to calculate the energy cost of running. Updated non-protein respiratory quotient equations[25] were used to estimate substrate utilisation (g.min^{-1}). The energy derived from each substrate was calculated by multiplying fat and carbohydrate utilisation by 9.75

kcal and 4.07 kcal, respectively.[26] Absolute energy cost was calculated as the sum of the energy derived from fat and carbohydrate for each submaximal running speed ≤LTP, and with an RER value of <1.00, in order to ensure an insignificant anaerobic contribution to energy expenditure. Running economy was expressed in (kcal·kg^{-1}·km.$^{-1}$).

Data Analysis

Each participant's energy cost-running speed relationship was fitted with a 3rd order polynomial function for all speeds <*s*LTP in order to interpolate their energy cost at relative submaximal speeds, which was assessed in 5% increments from 50% and 70% *s*LTP for the elite and recreational groups, respectively. In all cases the 3rd order polynomial function provided a good fit to the experimental data (R^2=0.948±0.060).

To verify the use of linear ratio scaling of energy cost measurements (i.e., kg^{-1}) in the current population, as indicated by our previous work,[8] plots of body mass against energy cost were fitted with both power and linear ratio functions. The power function revealed exponents close to unity (males, 0.96; females, 1.13), indicating that a linear ratio, which involves an exponent of 1.00, is appropriate. Furthermore, the linear ratio and power functions produced similar R^2 values (Males: [Linear; 0.56 vs. Power; 0.57], Females: [Linear; 0.72 vs. Power; 0.73]), and root mean square error (Males: [Linear; 5.41 vs. Power; 5.43], Females: [Linear; 4.43 vs. Power; 4.42]) values. The appropriateness of the linear ratio scaling was also confirmed by the absence of any relationship between body mass and energy cost per kg (linear ratio scaled) for males (both; r=-0.033, *P*=0.821) and females (both; linear; r=0.171, *P*=0.244). Consequently, relative expressions of energy cost were linear ratio scaled to BM^{-1} in all further analyses.

Statistical Analysis

An independent samples one-way ANOVA was used to investigate anthropometric and physiological differences between groups. A one-way ANOVA was used to investigate differences in energy cost according to sex (males vs. females). The influence of speed (absolute: [8-12 km.h^{-1} for recreational; 8-17 km.h^{-1} for high-level] and relative: [70-95% *s*LTP for recreational; 50-95% *s*LTP for high-level] on energy cost was investigated using one-way ANOVAs with repeated measures (RM). A two-way RM ANOVA (speed x performance standard) was used to consider differences in energy cost according to performance standard (high-levele vs. recreational). Post hoc analysis with Bonferonni adjustment was used to identify the origin of any significant difference. An independent samples *t*-test was used to determine whether the most economical running speed was different between the elite and recreational groups. All data are presented as mean ± SD. Statistical analysis was performed using SPSS version 22 (SPSS Inc., Chicago, Illinois, USA) with significance set as $P<0.05$.

RESULTS

Male and female runners classified as either high-level or recreational were of similar running standards, indicated by similar proximities to the sex-specific 10-km road world record time (Table 1). Males had a greater $\dot{V}O_2$max, *s*LTP, height, body mass, and body mass index (BMI) relative to females (Table 1). The performance standard of the high-level males and females in comparison to the recreational groups was emphasised by their percentage of 10-km road world record times, as well as their higher $\dot{V}O_2$max and *s*LTP values.

Sex and Energy cost

There were no sex differences in the energy cost of running for the recreational runners at 8-12 km·h^{-1} (P=0.289; Figure 1A), or high-level runners at 8-17 km·h^{-1} (P=0.766; Figure 1B). Similarly, no differences were observed between males and females within either group (i.e., recreational and high-level) when the energy cost of running was compared at relative speeds (Recreational, 70-95% *s*LTP; Elite, 50-95% *s*LTP) (Figure 1C, 1D; P=0.338; P=0.937, respectively). Given the similarity between male and female data the two sex groups were considered together in subsequent analyses.

Speed and Energy Cost

There was a speed effect on the energy cost of running for the high-level and recreational running groups (Figure 2). For the high-levelgroup, as absolute speed increased there was a decrease in the energy cost of running for each 1 km·h^{-1} increment between 9 km·h^{-1} and 11 km·h^{-1} (all P<0.001). A plateau was evident between 11 and 16 km·h^{-1} (P>0.05), and an increase in energy cost was observed between 16 and 17 km·h^{-1} (P<0.01). The nadir of this relationship, and thus the most economical running speed, occurred at 13 km·h^{-1}, which was 14% more economical than running at 8 km·h^{-1} and 3% more economical than running at 17 km·h^{-1}. For the recreational group, the energy cost of running decreased with each increment in running speed (8-12 km·h^{-1}; all P<0.001).

Similar relationships were observed for both high-level and recreational runners when the speed-energy cost relationship was considered for relative running speeds (i.e., % *s*LTP). The high-level group exhibited a decrease in energy cost (50-70% *s*LTP; all P<0.001) until the attainment of a plateau (70-80% *s*LTP, P>0.05), and a subsequent increase in energy cost (80-95% *s*LTP; all P<0.001). The nadir and most economical speed occurred at 70% *s*LTP, which was 9% more economical than at 50% *s*LTP. In the recreational group, the energy cost of running progressively decreased (70-85% *s*LTP; $P<0.001$), to attain a plateau (85-95% *s*LTP). The most economical running speed for the recreational group was 90% *s*LTP, a 4% improvement in running economy relative to running at 70% *s*LTP. Expressed as a % *s*LTP, the most economical running speed was significantly greater for the recreational (90 ± 10% *s*LTP) relative to the high-level (70 ± 10% *s*LTP) group ($P<0.001$).

Performance standard and Energy Cost

Significant differences in the energy cost of submaximal running were observed between the high-level and recreational groups for both absolute and relative running speeds ($P<0.001$; Figure 3). Comparing the absolute speeds common to all runners (i.e., 8-12 $\text{km}\cdot\text{h}^{-1}$; $n=92$) the high-level group (0.97 ± 0.09 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$) were ~8% more economical than the recreational group (1.06 ± 0.09 $\text{kcal}\cdot\text{kg}^{-1}\cdot\text{km}^{-1}$). Similarly, the high-level group were more economical (7-17% lower) at all relative speeds (70%-95% *s*LTP) than the recreational group, although this difference was greatest at 70% *s*LTP (17%).

DISCUSSION

The current study assessed the energy cost of running in a large sample of runners, across a wide range of absolute and relative speeds to determine the influence of sex, speed and performance standard. The principle findings of this study were that: 1) there was no sex-dependent difference in the energy cost of running at the same absolute or relative (% *s*LTP) running speeds for males and females of equivalent standard; 2) for high-level runners there was a “u-shaped” relationship between absolute and relative running speed and energy cost with the most economical speed being 13 $\text{km}\cdot\text{h}^{-1}$ (absolute) or 70% *s*LTP (relative), and; 3) high-level endurance runners had a lower energy cost, thus a better running economy at each absolute and relative (% *s*LTP) running speed.

Speed

The results demonstrated that running economy is influenced by running speed, with high-level runners examined across a wide-range of running speeds (8-17 km·h^{-1}; 50-95% *s*LTP) exhibiting "u-shaped" absolute and relative speed-energy cost relationships, with the most economical running speed being 13 km·h^{-1} or 70% *s*LTP. In contrast, for the recreational group energy cost decreased with speed until the highest common speed that valid energy cost measurements (<LTP and RER <1.00) could be obtained for all of these participants, which restricted these measurements to a much smaller range of speeds than the elite group (8-12 km·h^{-1}; 70-95% *s*LTP). The curvilinear energy cost-speed relationship observed for the high-level group is consistent with some preliminary reports (n=9);[10,11] that also considered measurements over a wide range of speeds, and whilst a number of other studies have typically reported linear or no speed-energy cost relationships this appears attributable to a much more limited range of speeds.[6-8] For example, when comparing across a similar range of speeds to our previous work, the last 4 speeds before *s*LTP,[8] we also observed a greater energy cost for running, thus poorer running economy, as speed increased (Figure 2C). An optimal movement speed for walking has long been documented,[27] and the current study provides convincing evidence that this is also the case for running. Although there was only a small (~4%) difference between the most economical running speed and 95% *s*LTP, these findings may be practically meaningful to an ultra-marathon competitor for instance, since a 65 kg male has been shown to expend ~6000 kcal per day during a 2-wk event.[28]

Interestingly, when considered relative to the *s*LTP, the most economical running speed for the recreational cohort (90% *s*LTP) was greater than that for the high-level cohort (70% *s*LTP). This difference might suggest an absolute biomechanical speed-effect limiting the most economical speed in the high-level group to a relatively low speed (70% *s*LTP, 13 km·h^{-1}) despite their physiological capacity to run at faster speeds (*s*LTP ≥17 km.h^{-1}). Furthermore, the most economical running speeds reported in the present study are similar to those reported by Steudel-Numbers and Wall-Scheffler[11] and Willcockson et al.[10] (~3.5 m.s^{-1}, 12.6 km·h^{-1}). Further research is necessary to understand the factors that regulate the most economical running speed, and the trainability of this speed.

Sex

The findings of this study demonstrated that there was no sex-specific difference in running economy, measured as energy cost per unit mass and distance (kcal·kg^{-1}·km^{-1}), for males and females of equivalent performance standard. These findings are in agreement with some[7,16], but not other previous studies.[12-15] The differences between studies may be explained by several methodological limitations, including: the assessment of oxygen cost to determine running economy,[12-16] which may be confounded by differences in substrate utilisation[6,8]; and lack of control for performance standard.[12-16] The present study accounted for these potential confounders by determining the energy cost of running, and comparing male and female runners of equivalent high-level and recreational performance standards.

Performance standard

Despite differences in its assessment, running economy has consistently been shown to be influenced by performance standard, with runners of a better performance standard being more economical.[17,18] The findings of the current study support those of earlier research and demonstrate that a high-level group of runners were more economical at each absolute (~9%) and at each relative (~7% to 13%) running speed compared to the recreational group (Figure 3). This difference could be due to both innate characteristics (e.g., calcaneus length;[29]

muscle-tendon morphology[30]) and differences in training. For example, running regularly for >6 months has been shown to improve running economy[31], which may be related to preferential changes in running technique,[32] muscle energetics[33] and/or body composition.[34]

Limitations

It is important to acknowledge the presence of an additional slowly developing component to the O_2 cost, termed the $\dot{V}O_2$ slow component, at all speeds above the lactate threshold.[35] Due to the large number of stages within the current protocol each stage was of a relatively short duration (4 min), whereas, the full manifestation of the $\dot{V}O_2$ slow component and thus attainment of a true submaximal steady-state may take up to 20 min[35]. Thus the current study was unable to fully account for the influence of the $\dot{V}O_2$ slow component on the energy-cost speed relationship. However, as the amplitude of the $\dot{V}O_2$ slow component is known to be greater at higher speeds/intensities between the LT and LTP (i.e., heavy intensity domain[36]) it is likely that the current protocol underestimated the energy cost at higher speeds, in which case the ascending limb of the speed-Ec relationship (13-17 $km \cdot h^{-1}$ in the high-level runners) may rise more steeply than we have documented. Future research could use a reduced number of stages of longer duration, or repeated test sessions, in order to more fully investigate the ascending limb of the speed-Ec relationship. We also recognise that substrate metabolism and thus potentially energy cost may be influenced by other variables, for example: prior exercise[37]; nutrition[38]; and temperature[39,40]. Hence participants were instructed to attend the laboratory after 36 h without strenuous exercise, following their habitual nutrition, and ran in the laboratory in standardised conditions.

Practical Applications

The speed-energy cost relationship documented in the current study indicates that measurements at different speeds are not comparable. Given that energy cost was sensitive to differences in both absolute and relative speed it raises the question whether measurements should be made at the same absolute or relative speed. This is likely to depend on the nature of the question under investigation; however, in the majority of cases we would recommend the use of the same absolute running speed so that the prescribed task is consistent for all participants and pre/post interventions. Furthermore, future studies should be mindful that male and female energy cost values are comparable, and could be considered together/interchangeably but performance standard clearly influences energy cost, which might suggest distinct consideration of this variable in some studies.

Conclusion

In conclusion, the findings of this study demonstrate that when running economy is expressed as the energy cost of running, there is a “u-shaped” relationship with speed; there is no sex-specific difference; and, high-level endurance runners exhibit a better running economy than recreational endurance runners. Due to the influence of speed on energy cost it is recommended that future investigations primarily compare energy cost measurements at the same absolute running speed. Identification of the most economical running speed may be of importance to ultra-endurance athletes, and factors governing this speed and its trainability warrant further investigation.

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Figure Legends

Figure 1 The effect of sex on running economy. Males (white circles) and females (black circles) are shown at the same absolute (panels A and B) and relative (panels C and D) speeds for the recreational (panels A and C) and high-level (panels B and D) groups. At absolute speeds (i.e., panels A and B) positive error bars are displayed for the male group, and negative error bars are displayed for female group. At relative speeds (i.e., panels C and D) positive error bars are displayed for the female group and negative error bars are displayed for the male group.

Figure 2 The effect of speed on running economy for the recreational (panels A and C) and high-level (panels B and D, n=24) runners at the same absolute (panels A and B, n=68) and relative (panels C and D) speeds. *Statistically significant differences between speeds (*P*<0.05).

Figure 3 The effect of performance standard on running economy at the same absolute (panel A) and relative (panels B) speeds for the high-level (solid line, black circle markers, n=24) and recreational (solid line, white circle markers, n=68) groups. *Statistically significant between group difference (*P*<0.05).

Table 1 Physiological and anthropometrical characteristics for elite and recreational runners.

		n	**Age (y)**	**Height (m)**	**Body Mass (kg)**	**BMI (kg.m^{-2})**	***s*LTP (km.h^{-1})**	**$\dot{V}O_2$max (ml.kg.min^{-1})**	**% 10 km Road World Record**	**Training mileage (miles.wk^{-1})**
High-level	**Male**	14	27 ± 7	1.80 ± 0.06$^{\#}$	67.3 ± 6.8$^{\#}$	20.8 ± 1.4*$^{\#}$	19.0 ± 1.0$^{*\#}$	69.5 ± 5.4*$^{\#}$	113 ± 2*	70 ± 20$^{*\#}$
	Female	10	25 ± 4	1.67 ± 0.06$^{\#}$	52.1 ± 5.2$^{*\#}$	18.6 ± 1.0$^{*\#}$	18.0 ± 1.0$^{*\#}$	63.8 ± 4.5$^{*\#}$	113 ± 3*	52 ± 9$^{*\#}$
	Total	24	26 ± 6	1.75 ± 0.09	61.0 ± 9.8*	19.9 ± 1.7*	19.0 ± 1.0*	67.1 ± 5.7*	113 ± 2*	63 ± 19*
Recreational	**Male**	35	30 ± 7	1.78 ± 0.07$^{\#}$	69.5 ± 6.3$^{\#}$	21.9 ± 1.4$^{*\#}$	16.0 ± 2.0$^{*\#}$	59.1 ± 5.3$^{*\#}$	157 ± 17*	32 ± 17$^{*\#}$
	Female	33	29 ± 7	1.65 ± 0.08$^{\#}$	57.1 ± 6.5$^{*\#}$	20.9 ± 1.6$^{*\#}$	14.0 ± 1.0$^{*\#}$	52.1 ± 4.2$^{*\#}$	158 ± 13*	23 ± 12$^{*\#}$
	Total	68	29 ± 7	1.73 ± 0.09	63.5 ± 8.9*	21.4 ± 1.5*	15.0 ± 2.0*	55.7 ± 6.0*	157 ± 15*	28 ± 15*

Post hoc differences ($P<0.05$) for performance standard are denoted * and within group differences for sex are denoted by $^{\#}$

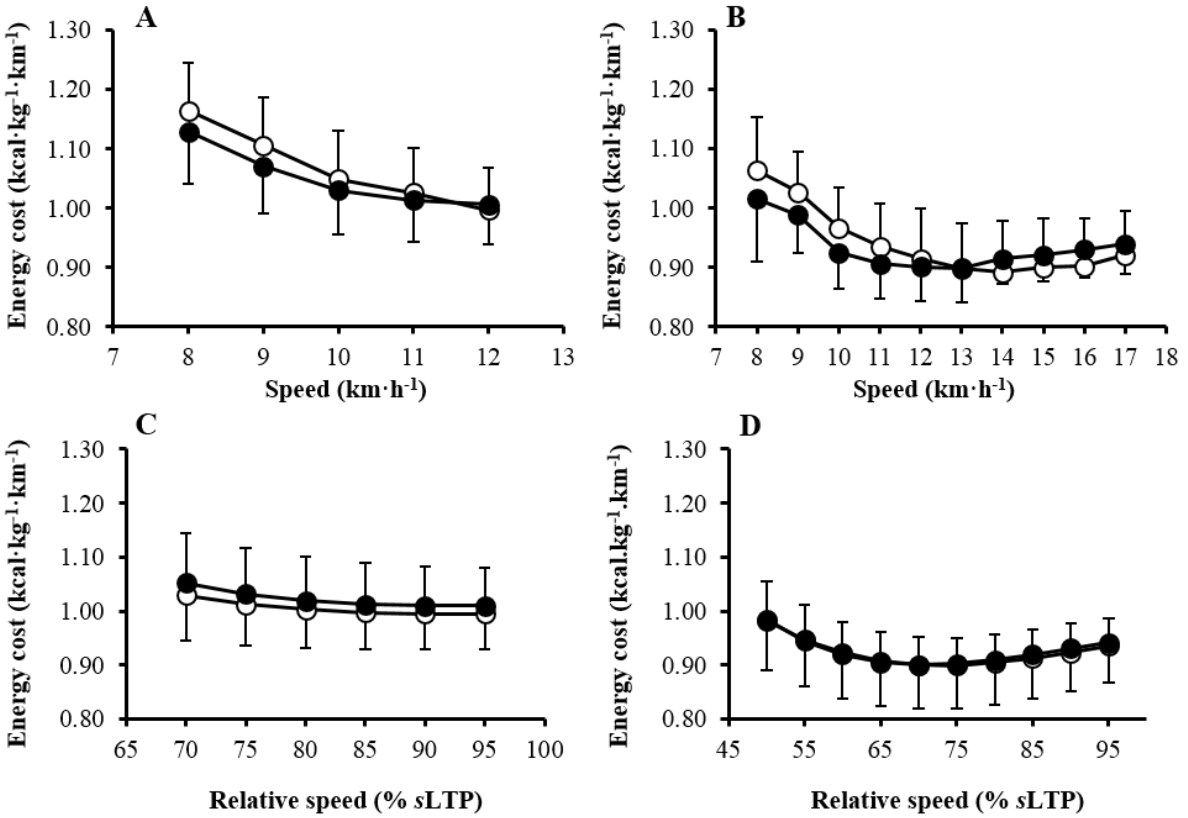
A
B
C
D
Energy cost (kcal·kg-1·km-1)
Energy cost (kcal.kg-1.km-1)
1.30
1.20
1.10
1.00
0.90
0.80
7
8
9
10
11
12
13
14
15
16
17
18
Speed (km·h-1)
65
70
75
80
85
90
95
100
45
55
Relative speed (% sLTP)

Figure 1

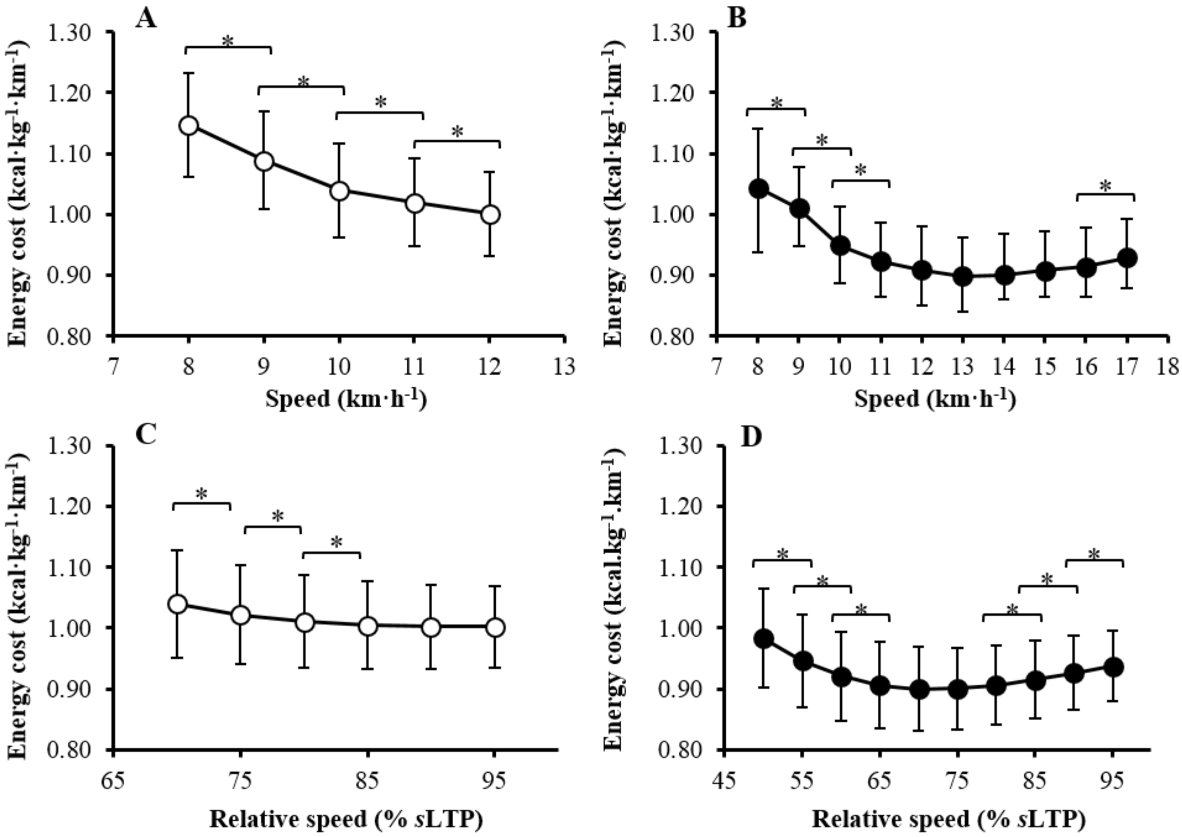
A
Energy cost (kcal·kg-1·km-1)
1.30
1.20
1.10
1.00
0.90
0.80
*
*
*
*
7
8
9
10
11
12
13
Speed (km·h-1)
B
Energy cost (kcal·kg-1·km-1)
1.30
1.20
1.10
1.00
0.90
0.80
*
*
*
*
7
8
9
10
11
12
13
14
15
16
17
18
Speed (km·h-1)
C
Energy cost (kcal·kg-1·km-1)
1.30
1.20
1.10
1.00
0.90
0.80
*
*
*
65
75
85
95
Relative speed (% sLTP)
D
Energy cost (kcal.kg-1.km-1)
1.30
1.20
1.10
1.00
0.90
0.80
*
*
*
*
*
*
45
55
65
75
85
95
Relative speed (% sLTP)

Figure 2

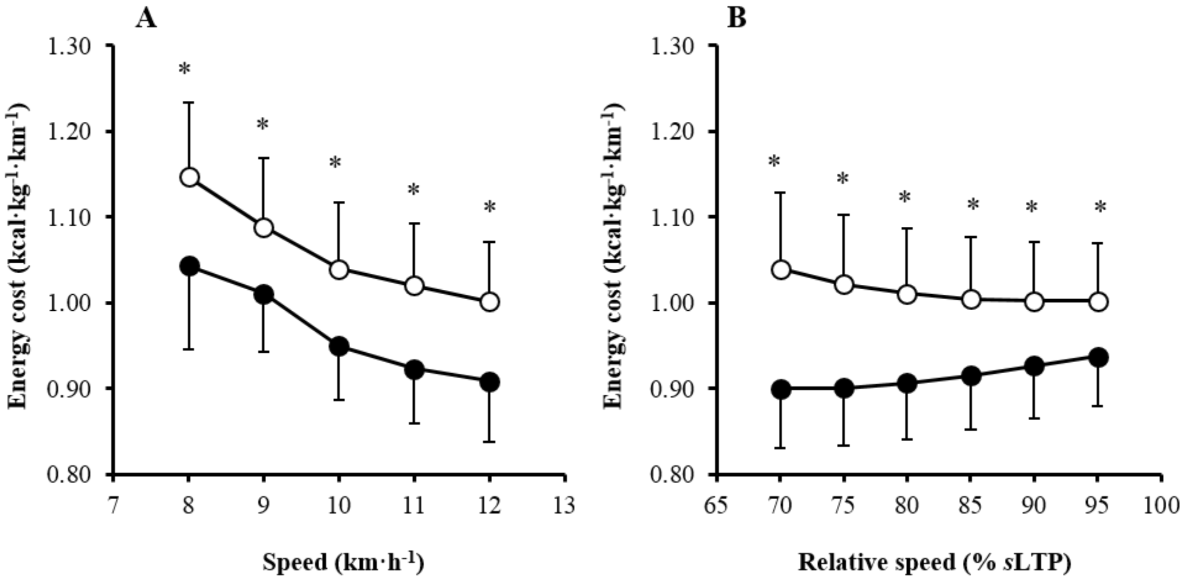
A
B
Energy cost (kcal·kg-1·km-1)
1.30
1.20
1.10
1.00
0.90
0.80
7
8
9
10
11
12
13
Speed (km·h-1)
65
70
75
80
85
90
95
100
Relative speed (% sLTP)
*

Figure 3