

Are there differences in running economy at different velocities for well-trained distance runners?

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Abstract The present study investigated whether there are differences in running economy at different velocities for well-trained distance runners, and to what extent a commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities affects the reliability of these measurements. Fifteen well-trained distance runners (9 male and 6 female) participated in this study. Gross oxygen cost of running (C_R), heart rate (HR) and $[La^-]_b$ during 5-min runs at velocities ranging from 8.0 to 17 km h⁻¹, representing intensities ranging from 60 to 90% of maximal oxygen consumption (VO_{2max}) was measured on two different days in random order. The athletes were also tested for lactate threshold, VO_{2max} and time to exhaustion at MAS (v_{MAS}). No significant differences in C_R between the different relative velocities or the different set velocities were found up to 90% of VO_{2max} . The incremental protocol for measuring VO_2 at different velocities was found not to

affect the reliability of these measurements. All athletes reached their VO_{2max} whilst running to exhaustion at MAS. The females showed significantly lower VO_{2max} , but significantly better C_R than the males. At velocities representing intensities between 60 and 90% of VO_{2max} , no differences in C_R were found. The commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities was found not to affect the reliability of these measurements. This means that C_R measured at sub-maximal velocities are representative for C_R at race velocity for distances above 10,000 m for most runners.

Keywords Oxygen cost of running · Running velocities · Test protocol

Introduction

Endurance performance, as in long distance running, imposes great demands on both the cardiovascular system and the employed locomotor organs. A model described by Pate and Kriska (1984) incorporates three major factors accounting for interindividual variance in aerobic endurance performance, namely maximal oxygen consumption (VO_{2max}), lactate threshold (LT) and work economy. This model is supported by numerous published studies (Pollock 1977; Farrell et al. 1979; Conley and Krahenbuhl 1980; Di Prampero et al. 1986; Bunc and Heller 1989; Helgerud 1994). Maximal aerobic speed (MAS), or the minimum speed needed to reach VO_{2max} (vVO_{2max}) has been explained by Morgan et al. (1989) as the VO_{2max} divided by C_R . Noakes et al. (1990) have shown that maximal speed reached during VO_{2max} testing correlates better with performances for distances between 10 and 90 km than VO_{2max} alone. In accordance with this, Lacour et al. (1990) found that C_R

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or VO_{2max} alone did not correlate with race velocity amongst well-trained middle and long distance runners (800–5,000 m), whereas MAS correlated well with the race velocity for distances longer than 800 m. The MAS has been found to represent 1,500–3,000-m velocity in elite and sub-elite distance runners (Lacour et al. 1990; Billat and Koralsztein 1996; Bassett et al. 2003). The time to exhaustion at MAS in these studies was approximately 3–9 min.

C_R is commonly defined as the steady rate VO_2 in $ml\ kg^{-1}\ min^{-1}$ at a standard velocity (Costill et al. 1973; Conley and Krahenbuhl 1980) or as energy cost of running per metre ($ml\ kg^{-1}\ m^{-1}$) (Di Pampero et al. 1986; Helgerud 1994; Helgerud et al. 2001). It is also expressed as mechanical efficiency, which is referred to as the ratio between work output and oxygen cost (Åstrand and Rodahl 1986).

Conley and Krahenbuhl (1980) and Helgerud (1994) have shown inter-individual variations in the oxygen cost of running (C_R). The causes of this variability are not well understood, but it seems likely that anatomical trait, mechanical skill, neuromuscular skill and storage of elastic energy are important factors (Pate and Kriska 1984). Inter-individual variability in C_R reflects the importance of this parameter for performance in long distance running. Inter-individual variability in C_R expressed as standard deviations (SD) is reported by Di Pampero et al. (1986) to be $\pm 8\%$, if the C_R is expressed per kg of body mass. This is in line with the results from Morgan et al. (1995) and Lacour et al. (1990). These results are also expressed per kg body mass.

Energy cost for movement does not increase in the same rate as body mass (Bergh et al. 1991; Eisenmann et al. 2001; Berg 2003). According to Helgerud (1994), a lack of allometric scaling will underestimate VO_{2max} and overestimate C_R amongst the heavier runners. Consequently, part of the variation in C_R in the experiments by Di Pampero et al. (1986); Morgan et al. (1995) and Lacour et al. (1990) are due to body mass differences. To use the allometric scaling when expressing C_R has seemed to reveal smaller differences. Helgerud (1994) has reported SD for C_R of approximately 5% within intermediate national elite marathon runners when expressing C_R per kg body weight raised to the power of 0.75 and metre. In accordance with this, Helgerud et al. (2001, 2003) have shown SD for C_R to be 5% in junior soccer players and 3–4% in adult players including a group of players at European Champions League level. Hoff et al. (2005) report SD for C_R to be $<5\%$ amongst 36 professional soccer players.

If measurements of C_R at a sub-maximal running velocity are to be used to evaluate race performance capacity amongst long distance runners, the measurements should be representative for the C_R at racing velocity. Previous investigations have shown C_R to be independent of running velocity up to intensities close to VO_{2max} for long distance runners (Di Pampero et al. 1986; Helgerud 1994). However

Daniels and Daniels (1992) report increasing C_R at increasing relative running velocities. They also found elite middle distance runners to have better C_R at velocities at or above marathon pace than elite long distance runners. The long distance runners had better C_R at velocities below marathon pace than the middle distance runners.

In most studies that have investigated C_R at different velocities, an incremental protocol with different sub-maximal work periods more than 3–10 min each, have been used (Di Pampero et al. 1986; Bunc and Heller 1989; Lacour et al. 1990; Helgerud 1994). A possible cause of error in these protocols is the incremental order in which the runs have been performed. In this context, it should be of interest to assess to what extent VO_2 at one velocity is affected by previously completed runs.

The aim of the present study was to investigate if there are differences in running economy at different velocities for well-trained distance runners, and to what extent a commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities affects the reliability of these measurements.

The hypothesis of the present study was

1. There are no differences in C_R at different velocities in male and female distance runners between 75 and 90% VO_{2max} .
2. The commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max} .

Materials and methods

Subjects

Fifteen moderately to well-trained runners, 9 males and 6 females, aged 29.3 ± 7.0 years, with an average VO_{2max} of $65.2 \pm 10.4\ ml\ kg^{-1}\ min^{-1}$ were included in the study, after giving their written consent to participate.

Test procedures

The subjects were tested on two different days, with a minimum of 1 day and a maximum of 7 days of rest or easy training in between. The first day consisted of measurements of heart rate (HR), blood lactate concentration ($[La^-]_b$) and oxygen consumption (VO_2) during 5-min runs (1.5% inclination) at different velocities until exhaustion. The subjects started with a velocity assumed to be about 60% of their VO_{2max} . This was either 8.0 or 9.5 $km\ h^{-1}$. After completing 5 min at this velocity, the speed was increased by 1.5 $km\ h^{-1}$ to the next 5-min work period. New steps were performed until the subject no longer could

Table 1 Test protocol for one of the runners

Step	Inclination (%)	Velocity (km h ⁻¹)	Duration (min s)
Day 1			
1	1.5	9.5	5
2	1.5	11	5
3	1.5	12.5	5
4	1.5	14	5
5	1.5	15.5	5
Rest for 60 min			
VO _{2max} test	5.2	12.5 → 17.5	6.50
Day 2			
1	1.5	15.5	5
2	1.5	14	5
3	1.5	12.5	5
4	1.5	11	5
5	1.5	9.5	5
Rest for 60 min			
MAS test	1.5	16.9	5.25

The table shows the protocol for one of the runners. The number of 5-min steps is individual, as well as the running velocities. Otherwise the protocol is the same for all runners

VO_{2max} maximal oxygen uptake, MAS maximal aerobic speed

complete 5 min at the desired velocity. After 60 min of rest, a VO_{2max} test was performed, using an incremental protocol at 5.2% inclination. The VO_{2max} test terminated at voluntary fatigue by the subjects. HR ($\geq 98\%$ predicted HR_{max}), R (≥ 1.05) and [La⁻]_b (≥ 8.0 mmol L⁻¹) values, as well as a possible plateauing of the VO₂ curve, was used to evaluate if VO_{2max} was obtained. LT and MAS were calculated on the basis of these measurements. The second day of testing consisted of measurements of HR, [La⁻]_b and VO₂ at the same velocities as the first day, but performed in the opposite order (i.e. starting with the highest running velocity after a warm up). Following a 60-min rest, the subjects then performed a run to exhaustion at MAS. The protocol for one of the runners is presented in Table 1.

Protocol for one of the runners (Table 1)

The VO₂ was measured using the metabolic test system, Sensor Medics Vmax Spectra (SensorMedics 229 CA, USA). The lactate measurements were performed using an Arkray Lactate Pro LT-1710 analyser (whole blood) (Arkray Inc. Kyoto, Japan). The LT was defined as the warm up [La⁻]_b value (i.e. measured after the lowest velocity in day 1) + 1.5 mmol. This is in line with the protocol proposed by Helgerud et al. (1990) consisting of several 5-min steps, at 1.5% inclination, increasing the speed by 1.5 km h⁻¹ after each step. The oxygen cost of running was measured at the same 5-min steps at 1.5% inclination. These steps were

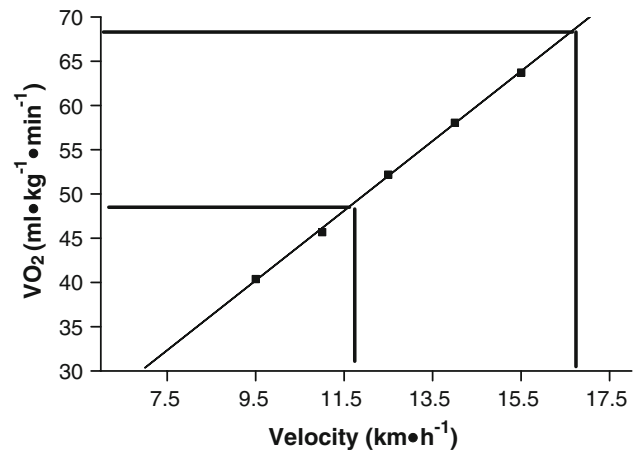


Fig. 1 Assessment of maximal aerobic speed. The linear regression equation in Fig. 1 is: $y = 3.9393x + 2.7963$, $R = 0.9997$, VO_{2max} for this runner is 69.2 ml kg⁻¹ min⁻¹. 70% VO_{2max} for this runner is 48.4 ml kg⁻¹ min⁻¹. From the equation, the corresponding velocity is 11.7 km h⁻¹, which equals 195 m min⁻¹. C_R expressed as ml kg⁻¹ m⁻¹ is thus 0.284 ml kg⁻¹ m⁻¹. MAS is the velocity point where the horizontal line representing VO_{2max} meets the extrapolated linear regression representing the sub-maximal VO₂ measurements. Here represented by a velocity of 16.9 km h⁻¹

performed until the subjects no longer managed to run for 5 min (exhaustion). In day 2, the same velocities were measured, but in the opposite order. C_R was calculated as gross oxygen cost per kilo bodyweight raised to the power of 0.75, per metre of running for the set running velocities. For the relative intensities, for example, 75% VO_{2max}, running velocity was calculated in the same way as for MAS (Fig. 1).

Assessment of MAS (Fig. 1)

Maximal aerobic speed was defined at the velocity at 1.5% inclination of the treadmill, where the horizontal line representing VO_{2max} meets the extrapolated incremental line representing the sub-maximal VO₂ measured in the LT assessment. By plotting VO₂ data against running velocity, individual regression equations for each subject could be obtained. Based on the findings of Helgerud (1994), values in between 60 and 90% VO_{2max} were used to calculate the incremental line. An example of the assessment of MAS is presented in Fig. 1.

Allometric scaling has been reported to decrease the SDs in C_R between subjects (Helgerud 1994; Helgerud et al. 2001; Hoff et al. 2005). VO₂ values are, thus, mainly expressed in ml kg^{-0.75} in the present study.

Statistical analysis

Descriptive statistical analyses were made to display means, standard deviations, standard error and coefficient of variance. To assess whether or not the VO₂ values would

be affected by the preceding step (i.e. the day to day measures described above), two-way ANOVA tests were used. Differences in C_R at different velocities and possible gender differences in C_R were also tested using two-way ANOVA tests. Linear regressions were made to display the equations representing the linearity between running velocity and oxygen cost of running. Correlations were calculated by the Pearson correlation test.

Results

Physical characteristics of subjects (Table 2)

Physical characteristics of the subjects are presented in Table 2. There was no significant gender differences in age, in LT velocity, in LT expressed as percentage of VO_{2max} or in $\dot{V}O_{2max}$. The male subjects were taller, heavier and had a higher VO_{2max} than the females.

To compare the physiological parameters at VO_{2max} and at MAS, only the participants that completed more than 5 min at MAS were included, independent of gender. They would, thus, have at least spent the same time at this intensity as at the set sub-maximal intensities. Further, 5 min should allow a possible steady rate to occur. These runners clearly reach their VO_{2max} at MAS (99.4% of VO_{2max}). Neither the results regarding HR nor $[La^-]_{b\ peak}$ were different being obtained at VO_{2max} or at MAS. However, the subjects exhibited significantly lower R values when running at MAS when compared with the R values achieved during the VO_{2max} test. These results are presented in Table 3.

Table 2 Physical characteristics of the subjects

	Males ($n = 9$)	Females ($n =$)
Age (years)	30.0 ± 9.2	27.8 ± 6.1
Height (m)	1.80 ± 0.06	1.68 ± 0.12*
Mass (kg)	76.9 ± 5.0	62.0 ± 11.2*
HR _{max} (beats min ⁻¹)	187 ± 8	190 ± 9
VO _{2max} (ml kg ⁻¹ min ⁻¹)	71.4 ± 6.3	56.2 ± 9.2*
VO _{2max} (ml kg ^{-0.75} min ⁻¹)	211.3 ± 17.8	157.8 ± 17.8*
R _{peak}	1.09 ± 0.03	1.08 ± 0.04
[La ⁻] _{b peak} (mmol l ⁻¹)	10.7 ± 1.8	9.8 ± 1.7
LT (km h ⁻¹)	13.7 ± 1.0	11.5 ± 1.6
LT (% VO _{2max})	82.6 ± 6.35	82.2 ± 2.4
MAS (km h ⁻¹)	16.5 ± 1.6	14.0 ± 1.9
Time _{MAS} (s)	432.5 ± 170.7	242.8 ± 92.0

Values are mean ± SD

HR_{max} maximal heart rate, VO_{2max} maximal oxygen uptake, LT lactate threshold, R_{peak} gas exchange ratio at VO_{2max}, [La⁻]_{b peak} highest blood lactate concentration reached during the VO_{2max} test, MAS maximal aerobic speed, Time_{MAS} time until exhaustion at MAS

* $P < 0.05$ significantly different from male values

Table 3 Physiological variables at VO_{2max} and at maximal aerobic speed (MAS)

	VO _{2max} ($n = 8$) 5.2% incl.	MAS ($n = 8$) 1.5% incl.
VO _{2max}	66.4 ± 8.8	66.0 ± 8.7
HR (beats min ⁻¹)	186 ± 7	185 ± 5
R	1.08 ± 0.04	1.02 ± 0.04*
[La ⁻] _{b peak} (mmol l ⁻¹)	10.5 ± 1.8	10.5 ± 2.4

Values are mean ± SD

VO₂ O₂ uptake, HR heart rate, [La⁻]_{b peak} blood lactate concentration

* $P < 0.01$ significantly different from VO_{2max} values

Physiological variables at VO_{2max} and at MAS (Table 3)

Table 4 shows the mean values in VO_2 at each of the set intensities by the ten subjects who completed at least 15.5 km h⁻¹, independent of gender. The results are divided into the two different test days. In day 1, the subjects ran at the lowest velocity first, increasing the speed for each separate run. In day 2, they started at the highest velocity, decreasing the speed for each separate run.

Oxygen cost of running at different test days (Table 4)

There were no significant differences in oxygen costs of running (C_R) expressed as VO_2 ml kg^{-0.75} min⁻¹ between the two test days. The coefficient of variation for the mean differences between days 1 and 2 is 0.9%. Consequently, only results from test-day 1, apart from the MAS results (day 2) are used in the following statistical analysis.

The mean data for C_R expressed as VO_2 ml kg^{-0.75} m⁻¹ at those of the set velocities that were completed by all the 15 subjects are shown in Table 5. These results are divided by gender.

Table 4 Oxygen costs of running at different test days

Velocity (km h ⁻¹)	VO ₂ ml kg ^{-0.75} min ⁻¹ ($n = 10$)		
	Day 1 (incremental)	Day 2 (descending)	Δ Day 2–day 1
9.5	117.6 ± 8.2	114.8 ± 7.7	-2.8 ± 6.5
11	135.8 ± 11.3	130.9 ± 12.1	-4.9 ± 5.7
12.5	153.4 ± 14.3	154.0 ± 14.7	0.6 ± 6.9
14	171.9 ± 14.8	176.4 ± 16.0	4.5 ± 8.6
15.5	187.2 ± 14.4	193.4 ± 14.5	6.2 ± 10.8

Values are mean ± SD

Incremental, velocities run in an incremental order

Descending, velocities run in a descending order

Table 5 Oxygen costs of running at set velocities

Velocity (km h ⁻¹)	VO ₂ ml kg ^{-0.75} m ⁻¹ Males (n = 9)	VO ₂ ml kg ^{-0.75} m ⁻¹ Females (n = 6)
9.5	0.753 ± 0.04	0.689 ± 0.027*
11	0.752 ± 0.053	0.686 ± 0.038*
12.5	0.749 ± 0.061	0.6757 ± 0.049*

Values are mean ± SD

* *P* < 0.01 significantly different from males

Table 6 Oxygen costs of running at relative intensities

Intensity in %VO _{2max}	VO ₂ ml kg ^{-0.75} m ⁻¹ Males (n = 9)	VO ₂ ml kg ^{-0.75} m ⁻¹ Females (n = 6)
75%	0.753 ± 0.049	0.684 ± 0.037*
80%	0.755 ± 0.051	0.681 ± 0.038*
LT	0.755 ± 0.055	0.672 ± 0.043*
85%	0.756 ± 0.054	0.677 ± 0.040*
90%	0.757 ± 0.056	0.675 ± 0.042*

Values are mean ± SD

* *P* < 0.01 significantly different from males

Oxygen cost of running at set velocities (Table 5)

There were no significant differences in C_R expressed as VO_2 ml kg^{-0.75} m⁻¹ between the different set velocities. The females had significantly lower C_R than the males at the set velocities. Mean interindividual variability expressed as standard deviations (SD) for the males was ±7.1%. For the females, mean interindividual variability was ±5.2%.

By plotting VO_2 data against running velocity as described in the protocol for assessing MAS, individual regression equations for each subject could be used to find the cost of running at the different relative velocities. Using running intensities representing 75–90% of VO_{2max} , the data are within the area of velocity completed by all the subjects. Table 6 shows the mean data for the C_R expressed as VO_2 ml kg^{-0.75} m⁻¹ at these velocities relative to VO_{2max} .

Oxygen cost of running at relative intensities (Table 6; Fig. 2)

No significant differences in oxygen costs of running expressed as VO_2 ml kg^{-0.75} m⁻¹ between the different relative velocities was found for the male or for the female subjects. The females had significantly lower oxygen cost of running than the males at all the relative velocities.

Discussion

The major findings in this study are that oxygen cost of running (C_R) did not differ for velocities between 75 and 90%

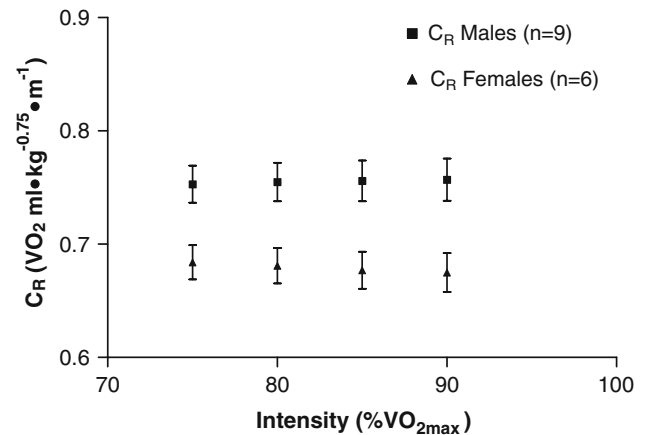


Fig. 2 Oxygen cost of running at relative intensities. Values are mean ± SD

VO_{2max} , and that the commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max} .

Cost of running at different velocities and intensities

The finding that C_R did not differ at the different set velocities or relative intensities is in agreement with reports from Di Pampero et al. (1986) and Helgerud (1994). These results are, however, not in agreement with the results from Daniels and Daniels (1992) who found increasing oxygen cost of running as relative running intensity increased in the area between 70 and 100% VO_{2max} . The results from the present study also revealed that the female runners had significantly lower C_R than the male runners at all different intensities. This is in accordance with the results from Helgerud (1994), but not with results from Daniels and Daniels (1992) or Bunc and Heller (1989). There were, however, only six females participating in the present study.

Reliability of the incremental protocol for assessing oxygen cost of running

When comparing the C_R from test-day 1 and test-day 2 using the two different protocols (incremental order day 1, descending order day 2), no significant differences were found. The coefficient of variation for the mean differences between days 1 and 2 is only 0.9%. Thus, it seems safe to assume that the commonly used incremental protocol for measuring VO_2 at different intensity levels is reliable up to 90% VO_{2max} .

Interindividual variability in oxygen cost of running

Interindividual variability in oxygen cost of running expressed as mean standard deviations for the three

velocities completed by all 15 subjects (SD) is $\pm 7.1\%$ for the males and $\pm 5.2\%$ for the females in the present study. The variability is lowest at the lowest velocity (9.5 km h^{-1}), and highest at the highest velocity (12.5 km h^{-1}). Interindividual variability is reported by Di Prampero et al. (1986) to be $\pm 8\%$, if the oxygen cost of running is expressed per kg of body mass. Morgan et al. (1995) and Lacour et al. (1990) have found within-group variations of about 20%. These results are also expressed per kg body mass. As energy cost for movement does not increase in the same rate as body weight, it seems likely that part of the variation in the oxygen cost of running in the experiments by Di Prampero et al. (1986), Morgan et al. (1995) and Lacour et al. (1990) is due to weight differences. If allometric scaling had been used, these results would presumably be more in line with those reported in the present study, since the use of allometric scaling when expressing running economy has revealed smaller differences (approximately $\pm 5\%$) in previous investigations (Helgerud 1994; Helgerud et al. 2001, 2003; Hoff and Helgerud 2003; Hoff et al. 2005).

Maximal aerobic speed

Eight of the fifteen subjects in our study completed more than 5 min at MAS, independent of gender. This group clearly reaches their $VO_{2\max}$ at MAS (99.4% of $VO_{2\max}$ at MAS). The results regarding HR and lactate confirm this. However, the subjects had significantly lower R values when running at MAS compared with the R values achieved during the $VO_{2\max}$ test. A possible explanation for this is the lower intensity at MAS than at the end of the $VO_{2\max}$ test.

We found a significant correlation between time at MAS and LT as percentage of $VO_{2\max}$ for the male subjects, but not for the females. With LT representing a higher percentage of $VO_{2\max}$, the anaerobic contribution to the work done per metre at MAS should logically be smaller.

Participating subjects

The participating subjects in the present study are characterised as a heterogeneous group with regards to running performance, $VO_{2\max}$ and C_R . However, they are all well-trained runners. Thus, it seems natural that the C_R by the group as a whole is higher than reported for elite runners (Daniels and Daniels 1992), intermediate national standard marathon runners (Helgerud 1994) and recreational marathon runners (Helgerud et al. 1990). The mean C_R amongst the males ($0.755 \text{ ml kg}^{-0.75} \text{ m}^{-1}$) corresponds to a CR of $0.246 \text{ ml kg}^{-1} \text{ m}^{-1}$, whereas the mean C_R amongst the females ($0.680 \text{ ml kg}^{-0.75} \text{ m}^{-1}$) corresponds to a CR of $0.243 \text{ ml kg}^{-1} \text{ m}^{-1}$. The present results are more in agreement

with the results from soccer players as reported by Helgerud et al. (2001) and by Hoff and Helgerud (2003).

Conclusion

At velocities representing intensities between 60 and 90% of $VO_{2\max}$, no differences in C_R were found. This means that C_R measured at sub-maximal velocities are representative for C_R at race velocity for distances above 10,000 m for most runners. The commonly used incremental protocol for measuring oxygen uptake (VO_2) at different velocities was found not to affect the reliability of these measurements.

Conflict of interest statement There is no conflict of interest.

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