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SHORT COMMUNICATION

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Determination of the velocity associated with the longest time to exhaustion at maximal oxygen uptake

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Abstract The so-called velocity associated with $\dot{V}O_{2\,max}$, defined as the minimal velocity which elicits $\dot{V}O_{2\,max}$ in an incremental exercise protocol ($v_{\dot{V}O_{2\,max}}$), is currently used for training to improve $\dot{V}O_{2\,max}$. However, it is well known that it is not the sole velocity which elicits $\dot{V}O_{2\,max}$ and it is possible to achieve $\dot{V}O_{2\,max}$ at velocities lower and higher than $v_{\dot{V}O_{2\,max}}$. The goal of this study was to determine the velocity which allows exercise to be maintained the longest time at $\dot{V}O_{2\,max}$. Using the relationship between time to exhaustion at $\dot{V}O_{2\,max}$ in the all-out runs at 90%, 100%, 120% and 140% of $v_{\dot{V}O_{2\,max}}$ and distance run at $\dot{V}O_{2\,max}$, the velocity which elicits the longest time to exhaustion at $\dot{V}O_{2\,max}$ (CV′) was determined. For the six subjects tested (physical education students), this velocity was not significantly different from $v_{\dot{V}O_{2\,max}}$ (16.96 ± 0.92 km · h^{-1} vs 17.22 ± 1.12 km · h^{-1}, $P = 0.2$ for CV′ and $v_{\dot{V}O_{2\,max}}$, respectively) and these two velocities were correlated ($r = 0.88$, $P = 0.05$).

Key words Maximal oxygen uptake · Exercise · Fatigue

Introduction

For exercise intensities above the intensity which corresponds to the velocity-time asymptote (or critical velocity: CV; Monod and Scherrer 1965), it has been found that a slow component of the oxygen uptake ($\dot{V}O_2$) kinetics becomes manifest some 80–110 s following the onset of exercise (Whipp and Wasserman 1972; Gaesser and Poole 1996). One marked consequence of this slow component is that it creates a broad range of exercise intensities at all of which maximal oxygen uptake ($\dot{V}O_{2\,max}$) will occur, provided that the exercise is continued to the point of fatigue (Astrand and Saltin 1961). Therefore, the so-called velocity associated with $\dot{V}O_{2\,max}$ which has been defined as the minimal velocity at which $\dot{V}O_{2\,max}$ occurs in an incremental exercise protocol ($v_{\dot{V}O_{2\,max}}$) (Billat and Koralsztein 1996) would not be the sole velocity at which $\dot{V}O_{2\,max}$ occurs. Indeed, it has been shown that $\dot{V}O_{2\,max}$ can be achieved during exercise at constant power during a range of intensities which are higher or lower than that at which this occurs during incremental exercise (Whipp 1994). However, in that range of exercise intensities, there is one velocity which allows the longest time for exercise at $\dot{V}O_{2\,max}$ which could be defined as the asymptote in the time at $\dot{V}O_{2\,max}$-velocity relationship.

The purpose of this study was to determine the velocity which allows exercise to be maintained for the longest time at $\dot{V}O_{2\,max}$, to be defined as the critical velocity at $\dot{V}O_{2\,max}$ ($CV_{\dot{V}O_{2\,max}}$).

Since it has been shown that the time-velocity relationship is all-important in high-intensity exercise that leads to fatigue within 1–30 min (Gaesser and Poole 1996), the four all-out runs used to determine it in this study were from 1 to 15 min long (140%–120%–100% and 90% $v_{\dot{V}O_{2\,max}}$).

Methods

Subjects

Six students volunteered to participate in this study. Their mean age, mass and height were 20.7 (SD 1.4) years, 75.5 (SD 10.8) kg and 1.82 SD (0.08) m, respectively. Each subject took part in five experiments on separate days. All subjects gave informed consent and the approval of the local Ethics Committee was obtained for all the tests.

General details

The subjects ran in five exhaustion tests (on a track 400 m long) on separate days at the same time each day. The first test was to determine $\dot{V}O_{2\,max}$ and $v_{\dot{V}O_{2\,max}}$ and the second, third, fourth and

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fifth tests were all-out exercise sessions run at 90%, 100%, 120% and 140% of $v_{\dot{V}O_{2max}}$ to determine the time to exhaustion ($t_{lim\ 90,100,120,140}$) and the distance ($d_{lim\ 90,100,120,140}$) run at these velocities. Moreover, in each t_{lim} test the specific time to exhaustion and distance run at $\dot{V}O_{2max}$ were determined. All the subjects were encouraged to give a maximal effort.

Protocol for $\dot{V}O_{2max}$ and $v_{\dot{V}O_{2max}}$ determination

The initial speed of the runner was set at 8 km · h^{-1} and increased by 2 km · h^{-1} every 4 min. Each stage was separated by a 1-min rest during which a fingertip blood sample was obtained and analysed for lactate concentration (YSI 27, Ohio, USA). Oxygen uptake ($\dot{V}O_{2max}$) was estimated throughout each test using a telemetric system (Cosmed K2, Rome, Italy). Expired gas concentrations were averaged every 15 s. Before each test, the O_2 analysis system was calibrated using ambient air, which was assumed to contain 20.9% of O_2 (K2 instructions manual). The calibration of the turbine flowmeter of the K2 was performed using a 3-l syringe (Quinton Instruments, Seattle). The criteria used to determine $\dot{V}O_{2max}$ were a plateau in $\dot{V}O_2$ despite an increase in running speed and a heart rate (HR) in excess of 90% of the predicted maximal HR (Taylor et al. 1955). In this protocol of incremental exercise, $v_{\dot{V}O_{2max}}$ was the lowest running speed at which $\dot{V}O_{2max}$ occurred (Billat and Koralsztein 1996). The velocity of the lactate concentration threshold was determined from the relationship between blood lactate concentrations and velocity and corresponded to a marked steepening of the lactate curve around 3.5 mmol · l^{-1} (Aunola and Rusko 1984).

Protocol for determination of t_{lim} at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$ and for each determination of t_{lim} at $\dot{V}O_{2max}$

The t_{lim} tests were carried out in random order each separated by 2 or 3 days at the same time of day within 2 weeks. The subjects first exercised for 10 min at 60% $v_{\dot{V}O_{2max}}$ and then progressed to 90%, 100%, 120% or 140% $v_{\dot{V}O_{2max}}$. They had to maintain the required velocity as long as possible until they were exhausted to determine the appropriate t_{lim} and for each t_{lim}, the time spent at $\dot{V}O_{2max}$ ($t_{lim,\dot{V}O_{2max}}$). During each t_{lim} test, the time spent at $\dot{V}O_{2max}$ was determined as the time when $\dot{V}O_{2max}$ was at least equal to $\dot{V}O_{2max}$ minus 2.1 ml · min^{-1} · kg^{-1} as determined as the $\dot{V}O_{2max}$ in the incremental test. The $\dot{V}O_{2max}$ determined in the incremental test was compared with the peak $\dot{V}O_2$ reached in the t_{lim} test. The distance limit (d_{lim}) was calculated as the product of t_{lim} and the appropriate velocity. In the same manner, d_{lim} run at $\dot{V}O_{2max}$ was calculated as the product of the time run at $\dot{V}O_{2max}$ and the appropriate velocity.

CV determination

The CV, which has been shown to be the asymptote of the time-velocity relationship or the slope b of the relationship between d_{lim} and t_{lim} (Ettema 1966), was determined in two ways:

1. Computing the total running distance and the *total* time to exhaustion (t_{lim}) at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$

$$d_{lim} = bt_{lim} + a \quad (1)$$

where d_{lim} is the total distance run at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$, b is the critical velocity and a is the running capacity, i.e. the distance run using oxygen reserves and anaerobic metabolism.

2. Computing the distance and *only* time run at $\dot{V}O_{2max}$ in each test at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$, Eq. 1 becoming:

$$d'_{lim} = b't'_{lim} + a' \quad (1)$$

where d'_{lim} is d_{lim} run at $\dot{V}O_{2max}$, t'_{lim} is the time run at $\dot{V}O_{2max}$, b' is the velocity which allows running for longest time at $\dot{V}O_{2max}$ (CV′) and a' is the distance run at $\dot{V}O_{2max}$ using the myoglobin oxygen reserve.

Statistical procedures

Non-parametric Wilcoxon rank tests were used to test for significant differences in $\dot{V}O_2$ and HR in the incremental and t_{lim} tests and also in CV obtained from the total time at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$ ($v_{\dot{V}O_{2max,inc}}$) and from the time spent at $\dot{V}O_{2max}$ in each one of these all-out runs. A Spearman's correlation was calculated between the CVs. In all analyses, the level of significance was set at $P < 0.05$.

Results

The subjects' mean $\dot{V}O_{2max}$ was 60.6 (SD 5.9) ml · min^{-1} · kg^{-1}, and $v_{\dot{V}O_{2max}}$ was 17 (SD 1.1) km · h^{-1}. The lactate threshold occurred at 13 (SD 0.8) km · h^{-1} [76.5 (SD 0.3) % $v_{\dot{V}O_{2max}}$].

The mean t_{lim} at 90%, 100%, 120% and 140% $\dot{V}O_{2max}$ were 731 (SD 224), 333 (SD 116), 123 (SD 32) and 73 (SD 18) s, respectively. In these all-out runs, the time at for which $\dot{V}O_{2max}$ was maintained was 15.8 (SD 39), 190 (SD 87), 73 (SD 29) and 18 (SD 19) s in the 90%, 100%, 120% and 140% t_{lim} tests, respectively. Five subjects did not reach $\dot{V}O_{2max}$ in the t_{lim90} test (86% $\dot{V}O_{2max}$ for these five subjects) and 88.4% $\dot{V}O_{2max}$ (for $n = 6$). Three subjects did not reach $\dot{V}O_{2max}$ in the t_{lim140} test [95.4 (SD 10.6) % $\dot{V}O_{2max}$ only; Fig. 1]. The $\dot{V}O_{2max}$ reached in the t_{lim90} and t_{lim140} tests were significantly different from the $\dot{V}O_{2max}$ determined in the incremental test ($P = 0.02$ for both).

There was no significant difference between $\dot{V}O_{2max}$ reached in the t_{lim100} and t_{lim120} tests ($P = 0.91$ and $P = 0.17$). The d_{lim} at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max,inc}}$ were 3087 (SD 955), 1580 (SD 547), 696 (SD 169), 481 (SD 110) m, respectively. However, in each t_{lim} test, the distance run at $\dot{V}O_{2max}$ was only 70 (SD 172) m (t_{lim90}), 907 (SD 433) m (t_{lim100}), 425 (SD 167) m (t_{lim120}), 113 (SD 127) m (t_{lim140}). The maximal velocity for which $\dot{V}O_{2max}$ was maintained over the longest time was 100% $v_{\dot{V}O_{2max}}$. CV calculated using the total t_{lim} was

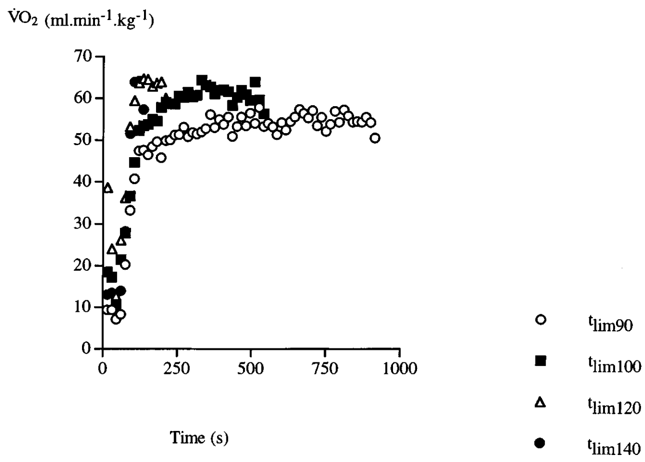

Fig. 1 A typical example of the time courses of oxygen uptake ($\dot{V}O_2$) during runs to exhaustion at 90%, 100%, 120% and 140% of the velocity at which maximal oxygen uptake was achieved in the incremental test ($t_{lim,90,100,120,140}$). Data from subject 6

significantly lower than CV computed using the time run at $\dot{V}O_{2\,max}$ (CV′) sustained in each of the all-out runs at 90%, 100%, 120% and 140% $\dot{V}O_{2\,max}$ [14.23 (SD 1.12) km · h^{-1} vs 16.96 (SD 0.92) km · h^{-1}, respectively $P = 0.02$]; (Fig. 2).

The constant *a* was significantly higher than *a*′ [216.1 (SD 59.2) and 28.9 (SD 19.2) m, respectively, $P = 0.04$]. Hence, CV′ calculated only using the time and distance run at $\dot{V}O_{2\,max}$ was not significantly different from $v_{\dot{V}O_{2\,max}}$ [16.96 (SD 0.92) km · h^{-1} and 17.22 (SD 1.12) km · h^{-1}, $P = 0.2$] and these two velocities were correlated ($r = 0.88$, $P = 0.05$). The CV was also significantly different from the velocity of the lactate threshold [14.1 (SD 1.1) km · h^{-1} and 13.0 (SD 0.8) km · h^{-1}, respectively, $P = 0.03$] but these two velocities were not correlated ($r = 0.72$, $P = 0.1$).

Discussion

One purpose of this study was to determine the velocity which allowed the longest time to be run at $\dot{V}O_{2\,max}$ (CV′). This was calculated using the slope of the time at $\dot{V}O_{2\,max}$ for four exhausting runs at 90%, 100%, 120% and 140% of $v_{\dot{V}O_{2max}}$ in the incremental test. This velocity was higher than the CV computed using d_{lim} and t_{lim} at 90%, 100%, 120% and 140% $v_{\dot{V}O_{2max}}$.

This can be explained by the fact that at 90% $v_{\dot{V}O_{2\,max}}$, five runners out of six did not reach their $\dot{V}O_{2\,max}$. Therefore, the average value of t_{lim} at $\dot{V}O_{2\,max}$ for the t_{lim90} run was very low (15 s). Consequently, t_{lim} and d_{lim} at $\dot{V}O_{2\,max}$ in t_{lim90}, t_{lim100}, t_{lim120} and t_{lim140} computed to determine CV′, were shorter than total times and distances to exhaustion at these velocities. The t_{lim} at $\dot{V}O_{2\,max}$ are also much lower for the 120% and 140% $\dot{V}O_{2\,max}$ runs (73 and 18 s, respectively). These lower t_{lim} induced an anti-clockwise rotation of the t_{lim}-d_{lim} relationship with an overestimation of CV′ and an underestimation of the *y* intercept of the t_{lim}-d_{lim} relationships calculated using only run times and distances at $\dot{V}O_{2\,max}$ (*a*′). Indeed, *a*′ is 10-fold shorter than *a* since the longest time at $\dot{V}O_{2\,max}$ was obtained when the subjects ran at $v_{\dot{V}O_{2\,max}}$, the velocity at which there was no accumulated oxygen deficit when the $\dot{V}O_{2\,max}$ steady state was reached (lasting 3 min 10 s for the t_{lim100} run). Hence, the CV calculated only using t_{lim} at $\dot{V}O_{2\,max}$ was not significantly different from $v_{\dot{V}O_{2max}}$ determined in the incremental test.

This result was in accordance with Monod and Scherrer (1965), who were the first to have considered that CV corresponded to a power output at $\dot{V}O_{2\,max}$. In the same way Ettema (1966) has considered that CV was close to the velocity at which $\dot{V}O_{2\,max}$ was achieved by world-class runners. Those authors were correct except that only the time spent at $\dot{V}O_{2\,max}$ for each power output should be taken into account and that it is impossible to maintain this velocity indefinitely.

The main criticism of this two-parameter critical power is the assumption made that the $\dot{V}O_{2\,max}$ is attained at the very onset of work (Morton and Hodgson 1996). This flaw is avoided when the distance is plotted against the time *after* the $\dot{V}O_{2\,max}$ has been attained.

The interest of this velocity, which allows $\dot{V}O_{2\,max}$ to be maintained for the longest time, is that it could be beneficial to train at the intensity of $\dot{V}O_{2\,max}$ for middle- and long-distance running (Billat and Koralsztein 1996).

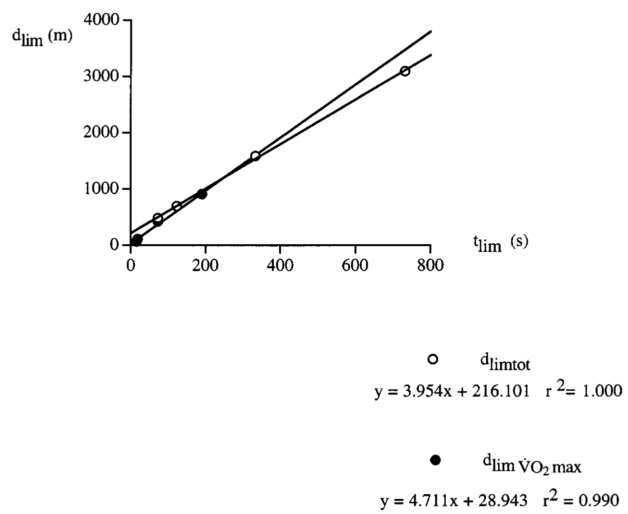

Fig. 2 A typical example of critical velocities calculated according to Eqs. 1 and 2. Average data of all the subjects. $t_{lim\dot{V}O_{2max}}$ and $d_{lim\dot{V}O_{2max}}$ are the time and distance run at maximal oxygen uptake ($\dot{V}O_{2\,max}$) during the time limit at 90%, 100%, 120% and 140% of the velocity at which $\dot{V}O_{2\,max}$ was achieved in the incremental test ($v_{\dot{V}O_{2max}}$). $t_{lim\dot{V}O_{2max}}$ is the time run at $\dot{V}O_{2\,max}$; t_{limtot} and d_{limtot} are the total time and distance run during the time limit at 90%, 100%, 120% and 140% of $v_{\dot{V}O_{2max}}$

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