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SHORT COMMUNICATION

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Effects of altitude on top speeds during 1 h unaccompanied cycling

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Abstract The present world record for 1 h unaccompanied cycling (55.291 km) was set by T. Rominger in November 1994 at sea level (Bordeaux, France). However, maximal aerobic cycling performances can be expected to increase at altitude because, for a given air temperature, air density decreases more than $\dot{V}O_{2max}$. The combined effect of these opposite trends results in an improvement of performances. In this study, based on the aerodynamics of track cycling, and assuming an average decrease of $\dot{V}O_{2max}$ with altitude as from the literature, we show that the ideal altitude for Rominger is 4000 m where he could cover 60.1 km in 1 h. To our knowledge, only two cyclists attempted at close time intervals to set the 1 h record at sea level and at altitude (Mexico, 2230 m above sea level): F. Moser and J. Longo. Their increase of performance with altitude was only about 50% of that predicted on the basis of similar calculations as performed on Rominger. This suggests that the decrease of $\dot{V}O_{2max}$ resulting from altitude is greater for athletes than for average trained subjects and/or that the fraction of $\dot{V}O_{2max}$ that can be maintained throughout 1 h decreases with altitude.

Key words Cycling · Altitude · Best performances · Energy cost of cycling

Introduction

On November 6, 1994, in Bordeaux Tony Rominger set the 1 h world record for unaccompanied cycling, namely 55.291 km. This extraordinary performance, and the preceding ones by himself (53.832 km), Indurain (53.040 km), Obree (52.713 km) and Boardman (52.270 km), were obtained at sea level. However, it is well known that cycling performances improve substantially at altitude. Furthermore, as shown by di Prampero et al. (1979), the effects of altitude on cycling performances can be calculated provided that the cyclist's maximal O_2 consumption, together with its reduction at altitude, are known. These authors have also shown that: (1) the optimal altitude ought to be in the order of 3.5–4.0 km above sea level, and (2) in an "evacuated" velodrome a hypothetical elite cyclist with a maximal O_2 consumption above resting of 5.34 l min^{-1} could cover 58.0 km in 1 h, pedalling in a pressurized suit providing him with a partial pressure of O_2 in the inspired air of about 150 mmHg (for a review, see di Prampero 1986). Apart from these unrealistic scenarios, the aim of this paper is to calculate the maximal distance that could be covered in 1 h by a cyclist with the same body size and maximal O_2 consumption ($\dot{V}O_{2max}$) as T. Rominger, riding the same bike on a similar velodrome at altitude. Additional assumptions will be that the performance takes place in the absence of wind at an air temperature of 20° C and that cycling posture is exactly the same as at sea level.

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Theory

The metabolic power ($\dot{V}O_2$) when cycling on flat terrain is given by:

$$\dot{V}O_2 = a\dot{s} + b v^2 \dot{s} \quad (1)$$

where s is the ground speed and v the air speed (in calm air, of course, $\dot{s} = v$), a and b are constants, and the metabolic power is expressed in O_2 consumption per unit of time (for practical purposes, the consumption of 1 l of O_2 yields 20.9 kJ). The first term of Eq. 1 is the power dissipated against the frictional losses in the tyres and drive train. The second term is the power dissipated against the air resistance, where the constant b is directly related to: (1) the drag coefficient (C_d), (2) the area projected on the frontal plane by the cyclist

(+ bike) (A_p), (3) the air density (ρ), itself a function of the barometric pressure and temperature (the small effects of humidity are disregarded) and inversely related to: (4) the mechanical efficiency of cycling (η):

$$b = 0.5\, C_d A_p \rho \eta^{-1} \quad (2)$$

It should be pointed out that, since $\dot{V}O_2$ in Eq. 1 is the metabolic power, the constant a also necessarily contains the efficiency. This can be stated formally by setting $a = a' \eta^{-1}$, where a′ is the constant relating the mechanical power dissipated against the frictional losses to the speed $\dot{s}$.

The maximal speed a cyclist can maintain over 1 h depends on his $\dot{V}O_{2max}$ and on the fraction of $\dot{V}O_{2max}$ that he can sustain throughout the effort (F). Thus, for maximal 1 h speed at sea level, Eq. 1 becomes:

$$F\dot{V}O_{2max} = a\, v_{sl} + b\, v_{sl}^3 \quad (3)$$

where it was assumed that $\dot{s} = v$, the subscript sl denoting sea level conditions. It is well known that $\dot{V}O_{2max}$ decreases with altitude. However, the reduced barometric pressure at altitude also leads to a decrease of the air density. Hence, since the efficiency of cycling at altitude is unchanged (Pugh et al. 1964; West et al. 1983), the constant b (Eq. 2) decreases in direct proportion to the air density. Therefore at altitude and in the absence of wind ($\dot{s} = v$), Eq. 3 becomes:

$$AF\dot{V}O_{2max} = a\, v_a + k\, b\, v_a^3 \quad (4)$$

where A and k are the fractional decreases of $\dot{V}O_{2max}$ and of the constant b due to altitude and the subscript a denotes altitude conditions. Substituting Eq. 3 into Eq. 4 and rearranging:

$$A(a\, v_{sl} + b\, v_{sl}^3) = a\, v_a + k\, b\, v_a^3 \quad (5)$$

The metabolic power dissipated against non aerodynamic forces at altitude and at sea level is rather close, because the speed difference between the two conditions is not very large: $A\, a\, v_{sl} \approx a\, v_a$. Furthermore, also at record speed, the metabolic power dissipated against non-aerodynamic forces is only about 5% of the total (Capelli et al. 1993). Hence, as a first approximation, the term describing the power dissipated against non-aerodynamic forces can be omitted. Therefore, simplifying and rearranging Eq. 5:

$$v_a / v_{sl} = \sqrt[3]{(A/k)} \quad (6)$$

it can be shown that the relative gain in speed at any given altitude can be obtained provided that A and k are known.

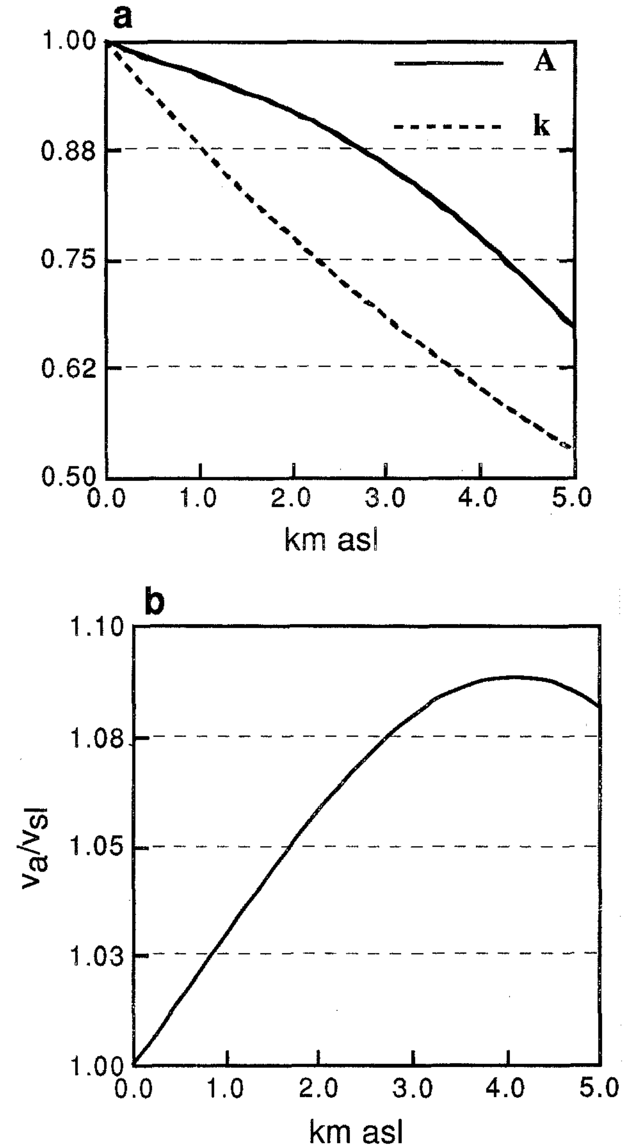

Fig. 1 **a** Fractional decreases of $\dot{V}O_{2max}$ (A) and of the constant b (k) (both normalized in respect to the values at sea level) as a function of the altitude above sea level (km); **b** ratio between speed at altitude (v_a) and at sea level (v_{sl}) as a function of the altitude above sea level 8 km)

Calculations

The decrease of $\dot{V}O_{2max}$ with altitude is rather well known from the literature (Cerretelli 1981), so that the factor A can be readily calculated for any given altitude (Fig. 1a). Since it was assumed here that air temperature and body posture (and thus the frontal area and drag coefficient) do not change between sea level and altitude, the constant k reduces to the ratio of the barometric pressures at altitude and at sea level (Fig. 1a). Thus, the ratio v_a/v_{sl} can be calculated: it is plotted in Fig. 1b as a function of the altitude. For example, in Mexico (2230 m above sea level) the ratio v_a/v_{sl}

amounts to 1.063, which would mean Rominger would cycle 58.8 km in 1 h.

Figure 1b shows also that, *ceteris paribus* and as originally pointed out by di Prampero et al. (1979), the optimum altitude is close to 4 km, not far from that of the Alto Irpavi velodrome (La Paz, Bolivia), where Rominger could cycle 60.1 km in 1 h.

Discussion

In a recent commentary on the record of Indurain, Snow and Drela (1994) pointed out that the ultimate cycling performances ought to be attained in a hypothetical velodrome wherein the cyclist could breath pure O_2 at a barometric pressure of 0.2 atm (=152 mmHg). However, a further improvement could be attained by reducing the pressure to 92 mmHg, i.e. to the O_2 partial pressure applying at 4.3 km altitude, at which $A = 0.75$. Taking into account the different molecular masses of pure O_2 and of average air, this yields $k = 0.134$. Hence, from Eq. 5, $v_a/v_{sl} = 1.775$ which would bring Rominger to the respectable speed of 98.14 km h^{-1}! All the above speculations were based on the assumptions that: (1) the metabolic power derived from anaerobic sources, (2) the power dissipated against non-aerodynamic forces, and (3) the fraction of $\dot{V}O_{2max}$ that can be maintained over 1 h (F in Eqs. 3 and 4) are the same at altitude and at sea level. The maximal amount of energy that can be derived from anaerobic sources in an elite athlete is in the order of 68 ml O_2 kg^{-1} (di Prampero et al. 1993). Therefore, their average fractional contribution to the overall metabolic power over 1 h can be calculated to be in the order of 1.3% at sea level. Hence, even substantial changes of anaerobic capacity cannot be expected to affect greatly the maximal metabolic power output at altitude. A slightly larger error can be introduced by assumption 2. Indeed, since the speed at altitude is greater than at sea level, disregarding the energy spent against non-aerodynamic forces (as done in Eq. 6) may lead to an overestimate of the velocity at altitude (v_a in Eq. 6) of about 1%. Finally, that assumption 3 may not true is suggested by the fact that the two cyclists (J. Longo and F. Moser) who attempted maximal 1 h performances at sea level and at altitude (Mexico) at short time intervals improved their performances only by about 50% of what is predicted by Eq. 6. This lesser than expected gain could also be due to the fact that the extremely high $\dot{V}O_{2max}$ of elite athletes may undergo greater decreases at altitude than measured in average trained subjects, in whom the values for the coefficient A were obtained. We hope that future performances by elite cyclists such as Obree, Broadman, Indurain and Rominger will throw additional light on this matter.

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