Energetics of best performances in track cycling

ABSTRACT

\( \dot{\text{VO}}_2 \text{max} \) and best performance times (BPTs) obtained during maximal voluntary trials over 1, 2, 5, and 10 km from a stationary start were assessed in 10 elite cyclists. Steady-state \( \dot{\text{VO}}_2 \) and peak blood lactate concentration ([La]b) were also determined in the same subjects pedaling on a track at constant submaximal speeds. The energy cost of cycling\( C_c \), J m\(^{-1}\)) was calculated as the ratio of \( \dot{\text{VO}}_2 \), corrected for glycolytic energy production and expressed in W, to \( v \) (m s\(^{-1}\)). Individual relationships between \( C_c \) and \( v \) were described by: \( C_c = C_{crr} + k' v^2 \) where \( C_{crr} \) is the energy spent against friction and \( k' v^2 \) is that spent against drag. Overall energy cost of cycling\( C_{ctot} \) was obtained, adding to \( C_c \) the energy spent to accelerate the total moving mass from a stationary start. Individual theoretical BPTs were then calculated and compared with the actual ones as follows. The maximal metabolic power sustained at a constant level by a given subject (\( E_{max} \), W) is a known function of the exhaustion time (\( t_e \)). It depends on his \( \dot{\text{VO}}_2 \text{max} \) and maximal anaerobic capacity; it was obtained from individual \( \dot{\text{VO}}_2 \text{max} \) and [La]b values. The metabolic power\( E_c \), W) necessary to cover any given distance (\( d \)) is a known function of the performance time over \( d \) (\( t_d \)); it is given by\( E_c = C_{ctot} v = C_{ctot} d t_d^{-1} \). For all subjects and distances, the \( t \) values solving the equalities \( E_{max} F(t_e) = E_c F(t_d) \) were calculated and assumed to yield theoretical BPTs. Calculations showed a fairly good agreement between actual and calculated BPTs with an average ratio of 1.035 ± 0.058.

It has been shown (25) that the best performances in track running over distances between 800 and 5000 m can be predicted with fairly good accuracy provided that the individual energy cost of running and the individual maximal metabolic power are known.

The model that makes this possible is discussed in detail in (25) and is summarized in the Appendix of this paper. In summary, the energy cost (\( C \)) represents the amount of energy required above resting to transport the runner’s body over one unit of distance and that the maximal metabolic power\( E_{max} \) is inclusive of the fraction derived from anaerobic energy stores utilization.

The aim of the present paper was to test the accuracy of the same model when applying it to track cycling, that is, to a type of locomotion whose energy cost (at variance with running) increases with speed. Hence we measured \( E_{max} \) and the overall energy cost of track cycling\( C_{ctot} \) as a function of the speed in a group of young, high level cyclists. This made it possible to calculate the theoretical best performance times over the distances of 1, 2, 5, and 10 km. The theoretical values were finally compared to the actual times measured during coeval racing trials over the same distances.

MATERIALS AND METHODS

http://ovidsp.tx.ovid.com/spa/ovidweb.cgi
Subjects. Ten male subjects, whose main physiologic and anthropometric characteristics are reported in Table 1, participated in the study. Two of 10 were professional road cyclists (L. N. and D. R.), whereas the others were competing in national-level amateur road races. The study was performed after the end of the racing season; however, the athletes maintained their usual training intensity during the entire period of the experiments. The subjects were thoroughly informed about the aims and details of the experimental protocol, which was approved by the Ethical Committee of the School of Medicine of the University of Udine, and were asked to sign an informed consent.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (yr)</th>
<th>BM (kg)</th>
<th>M (kg)</th>
<th>H (cm)</th>
<th>BS (m²)</th>
<th>VO₂max (L·min⁻¹)</th>
<th>[La]ₜₐₜ (mM)</th>
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<tbody>
<tr>
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<td>70.5</td>
<td>81.5</td>
<td>182.7</td>
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<tr>
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</table>

BM, body mass (kg); M, total mass, subject plus bicycle (kg); H, height (cm); BS, body surface (m²); VO₂max, maximal oxygen uptake (L·min⁻¹); [La]ₜₜ, Peak lactate concentration (mM) attained in the laboratory.

Energy cost of cycling. The energy cost of cycling at constant speed (Cₜₜ) was determined on all subjects riding traditional racing bicycles (weight = 10.2 kg ± 0.40) on the concrete surface racing track (341.42 m length) of Pescantina, 40 m above sea level (Verona, Italy). Each athlete used his own individual equipment in terms of frame and wheel size (27 inches). Tire size in all the cases was 27 x 18 mm and the inflation pressure was higher than 811 kP. The air speed was ≤ 1.5 m s⁻¹, the air temperature (T, K), and barometric pressure (Pb, mm Hg) were 307.0-297.6 K(34-24.6°C) and 759.0-753.0 mm Hg (101.2-100.5 kPa). Cₜₜ was calculated from the rate of metabolic energy expenditure divided by the speed, as discussed below.

The steady-state oxygen uptake (VO₂, L·min⁻¹) was measured by means of a telemetric, portable system (K2, COSMED, Italy). This system, whose accuracy has been assessed both in the laboratory and in the field (8,10,14), made it possible to measure VO₂ from pulmonary ventilation and from the oxygen fraction in mixed expired air without hindering the subject with cumbersome paraphernalia. Heart rate (HR) was continuously monitored by means of a portable heart rate monitor (Polar 3000, Polar Electro, Kempele, Finland) whose output was telemetrically transmitted and recorded.

The weight of the bicycle used by the subject was always assessed before each experimental trial. After 5 to 10 min of warm-up at 25-30 km·h⁻¹, the subject wore the mask with the impeller expiratory flow meter and the transmitting unit of the K2 system. The overall mass of the entire system did not exceed 900 g and the sensor, batteries, and transmitting unit were positioned on the subject’s back, i.e., without altering his frontal area. After the calibration of the oxygen sensor and the application of the heart-frequency monitor (Polar 3000, Polar Electro), the subject was instructed to start pedaling at 23 km·h⁻¹ (6.4 m·s⁻¹), as indicated by a tachometer (commercial type) mounted on the bicycle. In any case, the average time over each lap, and hence the actual average speed, was always measured by an operator with a stopwatch. After 3 min, the subject was asked to increase the speed by 3 km·h⁻¹. This procedure was repeated until the third minute at 41 km·h⁻¹ was completed. Pulmonary ventilation(VE BTPS, L·min⁻¹) and VO₂ were measured on a time basis of 15 s, and the values recorded during the third minute of each phase were averaged to yield the steady-state values. At the end of the phase at a nominal speed of 41 km·h⁻¹, the subject stopped and rested for 3 min. At the third minute of rest, 40 µL of capillary blood were withdrawn from the pre-warmed earlobe to assess blood lactate concentration ([La]ₜₜ) by means of a polarographic method(Microzym-L, SGI, Toulouse, France). After about 3.5 min, the subject resumed pedaling at a speed 3 km·h⁻¹ faster than the previous one. After the completion of the third minute at 44 km·h⁻¹, he stopped again and a second sample of blood was withdrawn. This procedure was repeated until the subject reached exhaustion. The highest actual speed sustained over the last 3-min period was 43.0 km·h⁻¹ (11.9 m·s⁻¹) on the
average (range 45.4 to 39.9 km·h⁻¹; 12.6 to 11.08 m·s⁻¹). The pedaling frequencies ranged from 108.8 at the highest to 62.9 rpm at the lowest speeds. In all cases, the subjects used a chain-ring with 53 teeth and rear sprockets of 19 teeth for speeds lower than 35 km·hr⁻¹, of 17 teeth for speeds between 35 and 38 km·hr⁻¹ and of 16, 15, or 14 teeth for the higher speeds.

When blood lactate concentration was negligible (<2.0 mM), the energy cost of cycling at constant speed was calculated from the ratio between steady-state \( \dot{V}O_2 \) above resting (mL O₂·s⁻¹) and average speed (m·s⁻¹). In turn, the resting \( \dot{V}O_2 \) was assumed to be equal to 5.0 mL·kg⁻¹·min⁻¹ (0.083 mL O₂·s⁻¹·kg⁻¹). Finally, the energy cost was expressed in J·m⁻¹, assuming that the energy equivalent of 1 mL O₂ STPD is 20.9 J (which is strictly true only if RQ = 0.96). When blood lactate concentration exceeded 2.0 mM, its contribution to the energy cost of cycling was calculated following the method of di Prampero et al. in running (25). Briefly, the net increase of lactate concentration in blood \( \frac{\Delta[La]}{b} \) was obtained subtracting the pre-exercise value, or the value attained at the lower speed, from the peak attained at the third minute of recovery. The energy equivalent of \( \frac{\Delta[La]}{b} \) was then calculated assuming that the increase of 1 mM of La in blood yields an amount of energy equal to the consumption of 3.0 mL O₂·kg⁻¹ (62.7 J·kg⁻¹) (22). Finally, the overall energy cost of cycling was determined by dividing the energetic equivalent of \( \frac{\Delta[La]}{b} \) by the overall distance covered and adding it to the aerobic cost.

Maximal oxygen uptake. Maximal oxygen uptake \( (-\dot{V}O_{2\text{max}}) \) was determined during an incremental exercise protocol on the cycle ergometer. The subjects reported to the laboratory (293 K, average ambient temperature) and, after being equipped with the heart rate monitor, started pedaling at 90 rpm at 150 W on a mechanically braked cycle ergometer (818 E, Monark, Varberg, Sweden). The handle bars, toe-clips, and saddle were replaced with the ones traditionally mounted on racing bicycles, and each subject adjusted the saddle height and the distance from the saddle and the handle bars to reproduce as close as possible his usual racing position. After 3-4 min the subject was asked to wear the nose clip and the mouthpiece; an operator initiated (and concluded) the collection of the expired gases into a Douglas bag. A second operator measured the collection time by means of a stopwatch. Collection times were always close to 60 s. After the first gas collection, the same set of measurements was repeated at 200, 250, and 300 W.

After the completion of the 300-W load, the subject remained seated on the cycle ergometer while the steady-state regression between heart rate and mechanical power was calculated and extrapolated to his maximal age predicted heart frequency. Then, the subject started pedaling at the workload corresponding to his theoretical maximal work rate and, after 3 min, the expired gases were collected for at least 30 s. At the third, fifth, and seventh minute of recovery after the final run, capillary blood samples were withdrawn from a prewarmed ear lobe to measure \([La]_b\).

The expired gas composition and volume were assessed using a paramagnetic O₂ analyzer (Oxylos 1-C, Leybold-Heraeus, Switzerland), an infrared CO₂ meter (BINDS 1, Leybold-Heraeus) and a dry gas meter (MCS, S.I.M. Brunt, Italy). The gas analyzers were calibrated before each experimental trial using gas mixtures of known composition.

Anthropometry. The body surface \( (BS, m^2) \) of the subjects was computed from body mass and stature following the method of Dubois and Dubois (7). The frontal area of each cyclist riding his racing bicycle \( (A) \) were obtained as suggested by Capelli et al. (3) and Swain et al. (30). Photographs were taken of the subjects on the bicycle in a racing posture with a rectangular surface of known area at their side. The outlines of the subjects and of the reference surface were then traced on paper, cut out, and weighed. The frontal areas were finally obtained, comparing the weight of the pictures of the cyclist and frame to the reference one.

Actual maximal speeds. The actual maximal speeds reached by the subject over the distances of 1024.3, 2048.6, 5121.3, and 10243.6 m (i.e., 3, 6, 15, and 30 times the complete track) were obtained during maximal tests (so called mock trials) 1 wk after the metabolic experiments on the track. Each subject performed two trials per day separated by at least 1 h of active recovery. The subjects rode the same bicycle used during the energy cost experiments and wore the same racing suits. They were asked to yield the best performance on each distance, and their heart rate was always measured throughout. After each session, the lactate concentration in the capillary blood from the ear lobe was assessed at the third, fifth, and seventh minute of recovery. This allowed us to obtain at least two indexes (HR and \([La]_b\)) of exhaustion and to tell whether the athlete had, or had not, approximated his maximal metabolic power output.

Best performance. The individual theoretical best performance times were calculated for each distance as follows (for further details see to the Appendix).

The maximal metabolic power a given subject can sustain during cycling \( E_{\text{max}} \) is a decreasing function of the time of exhaustion \( (t_e, s) \) (13,28,31). It is also proportional: 1) to his \( -\dot{V}O_{2\text{max}} \); 2) to the fraction of \( \dot{V}O_{2\text{max}} \) that can be sustained at constant level during exercise \( (F) \) and; 3) to his maximal anaerobic capacity \( A_NS \) equation [1] where MAP is the maximal aerobic power, i.e., \( -\dot{V}O_{2\text{max}} \) expressed in kW, and \( \tau \) is the time constant in seconds with which \( -\dot{V}O_{2\text{max}} \) is attained at muscular level at the onset of exercise.
The metabolic power requirement ($E_c$) necessary to cover any given distance ($d$) from a stationary start can be calculated as a function of the performance time ($t_d$, s) from the product of the overall energy cost of cycling ($C_{ctot}$) times the ground speed $s = d \cdot t_d^{-1}$: equation [2]

$$E_c = C_{ctot} \cdot s = C_{ctot} \cdot d \cdot t_d^{-1}$$  \[2\]

In turn, $C_{ctot}$ is the sum of two terms. The first is the energy cost of cycling at constant speed ($C_c$) equation [3] where $C_{crit}$ represents the energy spent per unit of distance against rolling resistance and ($k' v^2$) is the amount spent against the self-induced wind (24). The second term is the amount of metabolic energy spent, per unit of distance ($C_{kin}$), to accelerate the overall moving mass ($M$) from 0 to the final speed ($s$): equation [4]

$$C_c = C_{crit} + k' v^2 = C_{crit} + k' d^2 t_d^{-2}$$  \[3\]

$$C_{ctot} = C_c + C_{kin}$$  \[4\]

Thus, from equations 2, 3, and 4 equation [5]

$$\dot{E}_c = C_{crit} \cdot dt_d^{-1} + k' d^3 t_d^{-3} + C_{kin} \cdot dt_d^{-1}$$  \[5\]

The time values solving the equalities $E_{max}$ ($t_e$) = $E_c$ ($t_d$), assumed to yield the theoretical best performance times, can be easily calculated by means of an iterative procedure and compared with the actual ones.

Statistics. Linear regressions were calculated by means of the least-squares method (2). The agreement between the actual times and theoretical times of performance was evaluated calculating the ratios of the actual ($t_{act}$) to the theoretical times ($t_{theor}$) and the error (%) between $t_{act}$ and $t_{theor}$: equation [6]

$$\text{Error (%)} = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{|t_{act} - t_{theor}|}{t_{theor}} \right) \cdot 100$$  \[6\]

RESULTS

The results obtained in a typical subject (R.S.) show that -VO2 during constant speed cycling increased as a
curvilinear function of the speed and that, at speeds above 11 m·s⁻¹ (in this subject), blood lactate concentration [La]b increased markedly (Fig. 1). The VO₂ attained at the highest speed (11.9 m·s⁻¹ ± 0.57) during the test on the track amounted, on the average, to 4.6 L·min⁻¹ ± 0.70 (SD), i.e., to 85%± 13 of VO₂max. Mean blood lactate concentration and mean heart rate at the same exercise intensity were 8.9 mM ± 2.90 and 181 beats·min⁻¹ ± 8, respectively. The data reported in Figure 1 made it possible to calculate the energy cost of cycling at constant speed (C_c) on all subjects, as detailed in Methods. C_c is reported for this same subject in Figure 2.

![Figure 1: VO₂ (L·min⁻¹) and lactate concentration ([La]b, mM) as a function of the speed (m·s⁻¹). (Results on a typical subject RS).](image)

http://ovidsp.tx.ovid.com/spa/ovidweb.cgi
Figure 2-Energy cost of cycling at constant speed ($C_c$, J·m⁻¹) as a function of the square of the ground speed ($s^2$, m²·s⁻²). Regression is described by: $C_c = 0.84 \, s^2 + 16.73$; $r^2 = 0.989$. Subject RS.

Figure 2 shows, as expected on theoretical grounds and shown by previous studies (3,23,24,26), that the energy cost of cycling increases linearly with the square of the speed (mean $r^2$ of the individual linear regressions equalled 0.975 ± 0.025; N = 10): equation [7] where the two terms have been previously defined (see equation 3). The anaerobic lactacid contribution to $C_c$ was fairly low, amounting on the average to 4.4%(± 2.59) of the total.

$$C_c = C_{crr} + k' \, v^2$$  \[7\]

Equation 7

The $y$ intercept of linear regressions such as that of Figure 2 yielded the energy spent per unit distance against the rolling resistance ($C_{crr}$), and the slope of the same regression was the proportionality constant relating the energy expenditure per unit of distance to the square of the air speed ($k'$).

The values of $C_{crr}$ normalized by the total mass $M$, as determined from the individual regressions, are reported in Table 2. Their average value amounts to 0.31 J·m⁻¹·kg⁻¹± 0.170 (SD) in close agreement with that obtained by us in a previous study (3). The average values of the proportionality constant $k'$ obtained in the present study amounted to 0.72 J·m⁻¹·s²·m⁻² ± 0.133 (see Table 2), in good agreement with the values reported in literature for similar conditions (3,11,24). The barometric pressure and temperature prevailing during the test and the value of the area projected on the frontal plane ($A$, m²) are also reported in Table 2. These allowed us to calculate the drag coefficient ($C_d$) as follows: In equation 7 the proportionality constant $k'$ is a function of the air density [$\rho$], of $A$, of the dimensionless drag coefficient ($C_d$) and it is inversely related to the mechanical efficiency of cycling ([$\eta$]): equation [8] Rearranging equation 8 equation [9] It becomes apparent that the drag coefficient $C_d$ can be calculated from the experimentally determined values of $k'$, provided that $A$ and [$\rho$] (see below) are known and assuming a given value of [$\eta$]. In turn, if we ignore the minor effects of water vapor, [$\rho$] can be considered directly proportional to the barometric pressure ($P_b$, mm Hg) and inversely proportional to the absolute temperature ($T$, K): equation [10] where [$\rho_0$] is the density of dry air at 760 mm Hg and 273°K (1.293 kg·m⁻³).
TABLE 2. The values of the proportionality constant k', of the air temperature and of the barometric pressure are reported for the 10 subjects on whom the relationship between \( C_c \) and \( s^2 \) was determined. The calculated values of the ratio between \( C_{cr} \) and the total mass \( M \) and of the dimensionless drag coefficient \( (C_d) \) are reported as well (see text for details).

\[
k' = 0.5 \ \rho \ A \ C_d \ \eta^{-1} \quad [8]
\]

Equation 8

\[
C_d = 2 \ k' \ \eta(\rho \ A)^{-1} \quad [9]
\]

Equation 9

\[
\rho = \rho_0(P_B/760)(273/T) = 0.359 \ \rho_0(P_B/T) \quad [10]
\]

Equation 10

In conclusion, the drag coefficient \( C_d \) was obtained from the experimentally determined values of \( k' \) and \( A \), together with \( P_B \) and \( T \) prevailing during the test assuming that the cycling efficiency (\( \text{\eta} \)) was equal to 0.22 (29). The values are reported in Table 2. Again, these values are close to those reported elsewhere (3,11,24).

The times (\( t_d \), s) necessary to cover the indicated distances during the mock trials, the corresponding average speeds (\( s \), m \( \cdot \) s\(^{-1} \)), the heart rates attained in the final part of the test (HR), and the peak lactate concentrations in the blood after the end of the exercise ([La]\(_b\)), together with the environmental condition prevailing during the test (\( P_B \) and \( T \)), are reported in Table 3.
TABLE 3. Performance times (t) and speeds (s), gross peak lactate concentrations ([La]b), and heart rates (HR) determined during the maximal tests are reported along with the air temperature (T) and the barometric pressure (Pb) prevailing during the trials.

The amount of energy, in O2 equivalent, derived from anaerobic glycolysis during the mock trials was calculated by subtracting the pre-exercise values from the peak [La]b reported in Table 3. The net values were then converted into O2 as described in the methods section; they were 31.8, 34.5, 28.8, and 23.7 mL·O2·kg⁻¹ from the shortest to the longest distance, respectively.

As described in the methods section and explained in detail in the Appendix, the theoretical best times of performance were calculated determining, by means of a computerized iterative procedure, the time values for which Emax in equation 1 becomes equal to Ec in equation 5. This procedure was repeated for each subject and each distance substituting into equations 1 and 5 the appropriate values of the variables: MAP, AnS, F, Cctt, k', M, and d (for detailed calculations, see the Appendix).

The theoretical best performance times are plotted in Figure 3 as a function of the corresponding actual performance times obtained during the maximal mock trials. The two indexes of the goodness of fit are reported in Table 4. It can be seen that the average absolute error between theoretical and actual times of performance is less than 5%.
DISCUSSION

In the present study, best performance times in track cycling were calculated using a predictive model which was originally applied to middle distance running (25). The grand average of the absolute error between theoretical and actual times turned out to be less than 5%, i.e., on the same order as that previously obtained in running. This is worth emphasizing since in cycling we deal with a form of locomotion whose energy cost depends on the speed, whereas in running C is almost independent of the speed, at least in the range investigated in (25). However, for the shortest distance, the performance time is overestimated (albeit not significantly), whereas, for the three longer ones, the best performance times are systematically underestimated, the degree of underestimation increasing with distance (see Table 4). This may depend on systematic errors in the accuracy with which all the variables that enter in the calculations of $E_{\text{max}}$ and $E_c$ are assessed. We will therefore discuss them briefly, considering first the factors that enter into the calculations of $E_{\text{max}}$.

Maximal metabolic power ($E_{\text{max}}$). The accurate assessment of the individual $\dot{V}O_{2\text{max}}$, and hence of the corresponding MAP, can indeed influence the accuracy of the predictive model proposed. In this study it was assumed that $\dot{V}O_{2\text{max}}$ had been reached when at least two of the following three criteria were satisfied (15): 1) mean $RQ$ $\geq$ 1.10; 2) HR within 10 beats of the age predicted maximum and; 3) $[\text{La}]_o$ $\geq$ 10 mM.

A necessary prerequisite to obtaining $E_{\text{max}}$ is also the knowledge of the time constant with which $\dot{V}O_{2\text{max}}$ is attained at the onset of the maximal effort ($\tau$). In eq. 1. The values of $\tau$ used in the literature ranged from 10 s, as originally proposed by Wilkie (31) and used by di Prampero et al. (25), to 30 s according to Pérronet et al. (21). In the

<table>
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<th>Distance (m)</th>
<th>Error (%)</th>
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Values are means $\pm$SD; Error (%), absolute percent error between actual and calculated theoretical best performance times; $t_{\text{act}}/t_{\text{theor}}$, ratio of actual to calculated theoretical best performance times. Significant difference based on Student’s $t$ test ($H_0 = 1; H_a \neq 1$): * $P < 0.001$; $^P < 0.01$. Table 4. Error (%), see text) and ratio between actual and theoretical times of performance ($t_{\text{act}}/t_{\text{theor}}$).
present paper, it was assumed that \( \tau = 24 \text{s} \), as from data obtained by nuclear magnetic resonance spectroscopy (1).

These data show that at the onset of exercise the muscle phosphocreatine (PC) concentration decreases monoeXponentially with a time constant of 24 s. Since the rate of decrease of PC is assumed to be the mirror image of the rate of increase of \( \Delta \text{VO}_2 \) at the muscular level (4), it seemed appropriate to assume that \( \tau \) in equation 1 is also equal to 24 s. The third term of equation 1, containing the constant \( \tau \), leads to a decrease of \( E_{\text{max}} \) which, for a given set of values of \( F, \text{VO}_{2\text{max}} \), and \( \text{AnS} \), is directly proportional to \( \tau \) and inversely proportional to \( t_\text{ex} \). For \( \tau = 24 \text{s} \), the decrease of \( E_{\text{max}} \) in our experimental conditions ranged from about 20% for \( t_\text{ex} = 80 \text{s} \) to less than 3% for \( t_\text{ex} = 890 \text{s} \). Thus, the underestimate of \( t_\text{act} \) in the three longest mock trials may have been caused by an underestimation of \( \tau \). However, it can be calculated that, to bring \( t_\text{act} \) and \( t_\text{theor} \) to be equal, \( \tau \) ought to be 54, 66, 120, and 215 s in the three cases, respectively. Since these values are by far too large, it can be concluded that only a minor fraction (if any) of the underestimate of \( t_\text{theor} \) can be attributed to errors in the assumed value of \( \tau \).

In the present study the anaerobic contribution to the overall energy expenditure (AnS) expressed in \( \text{O}_2 \) equivalents amounted to 51.4, 54.1, 48.4, and 43.3 mL O\(_2\)·kg\(^{-1}\) from the shortest to the longest distance, respectively. These values are comparable with those reported by Gastin (9) for cycling. The above reported values of AnS resulted from the values of the lactic contribution of 31.8, 34.5, 28.8, and 23.7 mL O\(_2\)·kg\(^{-1}\), respectively (see Results and Table 3), plus the contribution of PC breakdown, which was assumed to be constant in each subject and equal, on the average, to 19.6 mL O\(_2\)·kg\(^{-1}\). Thus, the alactic contribution to AnS amounted to 38.1, 36.2, 40.5, and 45.3% from the shortest to the longest distance, respectively. In terms of metabolic power, the contribution of the anaerobic stores throughout the effort (AnS) was calculated from the sum of the energy released from La utilization, which was measured (see Table 3), plus the energy derived from PC splitting. It was also assumed that the entire amount of energy from PC breakdown, estimated from generally accepted literature values (5,12,21), was available independently of the exercise duration. However, Medbøe et al. (17) showed that the amount of PC split during exhaustive exercises lasting from 30 to 180 s, can be described by a mono-exponential function with a time constant close to 30 s (Fig. 1 (17)). It can therefore be calculated that in the present case at the end of the shortest trial ([almost equal to] 81 s), the energy derived from PC splitting would have been about 93% of the maximal alactic capacity, i.e., of about 7% less than here assumed. In turn, since the alactic fraction of AnS for the shortest distance amounted to 31.8%, the underestimate of AnS would have brought about a reduction of about 2.2% (0.07 \times 0.318 = 0.022) and hence of about 1% of \( E_{\text{max}} \cdot t_\text{ex} \).

Another crucial point for predicting performances is the need to use a factor representing the reduction of the fraction of \( \text{VO}_{2\text{max}} \) maintained throughout the effort (\( F \) in equation 1). To this aim, we followed the approach suggested by Péronnet (20,21) on the basis of data obtained on elite long distance runners (see Appendix). However, those values of \( F \) may have been too high for a group of amateur cyclists. Therefore, we have calculated \( t_\text{theor} \) for a subject whose characteristics were assumed to be identical to the average observed in this study, with the exception of \( F \) which was reduced by 5% as compared with the values used in this study for 10-km mock trials (0.957), the only distance in which \( F \) does play a substantial role. The theoretical times differed by less than 1%. These calculations show that \( F \) did play only a minor role in predicting \( t_\text{theor} \) in the longest distance.

Energy cost of cycling (Ec) and metabolic power requirement. The energy cost of track cycling was calculated measuring the \( \text{VO}_2 \) at the steady state by means of a portable system, which did not include the sensor for carbon dioxide. As a consequence, \( \text{VO}_2 \) was calculated assuming a constant R equal to 1.0, a fact which may lead to a slight overestimation of \( \text{VO}_2 \). However, the portable system adopted in the present study (K2) was shown to be reliable and
accurate both in the laboratory (10,14) and in the field (8), a fact that is supported by the good agreement between the values of $c_{cr}, k'$ and $C_d$ obtained in this study (Table 2) and those reported in the literature for comparable conditions (3,11,24,26). Furthermore, the K2 was positioned on the back of the subjects, a fact which may have introduced a systematic increase of $k'$ and $C_d$ in all subjects. Once again, however, the agreement between the present data and data from the literature suggests that the possible increase of $k'$ and $C_d$ a result of the use the K2 on the cyclists' back was within the background noise inevitably inherent in these type of measurements.

In the present study the air density was calculated without the relative humidity. However, as discussed in the Appendix, this did not lead to any appreciable effects on the calculated variables.

Moreover, it should be noted that $k'$ and $C_d$ apply strictly to subjects in fully dropped posture on traditional racing bikes. As such, they cannot be applied to other postures and/or aerodynamic frames and/or wheels. Finally, $C_d$ depends on the actual value of the mechanical efficiency, which was assumed to be 0.22.

In the calculation of the fraction of metabolic energy spent to accelerate the overall mass from 0 to the final speed ($C_{act}$), the mechanical efficiency of cycling was assumed to be equal to 0.22 (see Appendix). $C_{kin}$, as well as its ratio to the total energy spent ($C_{ctot}$), depends on the final speed attained by the athlete and on the overall distance covered (equation A4 in Appendix). For a mechanical efficiency equal to 0.22 and applying the average values of $c_{cr}$, $k'$, $M$, and $v$ of Tables 2 and 3, the ratio $C_{kin}/C_{ctot}$ amounts to 0.17, 0.091, 0.038, and 0.019 in the four distances. It can be calculated that, if the mechanical efficiency of transforming metabolic into kinetic energy is assumed to be 0.19 (instead of 0.22), the resulting ratios $C_{kin}/C_{ctot}$ become 0.192, 0.104, 0.044, and 0.022, respectively. This leads to an increase of the average $t_{theor}$ by 1.0, 0.5, 0.25, and 0.12% in the four distances of this study, thus indicating that the value of the assumed mechanical efficiency has only a minor effect on the theoretical times over the range of the studied speeds.

$$C_{kin} = 0.5 \cdot M \cdot s^{-2} \cdot (\eta \cdot d)^{-1}$$

Equation 10D

In the present study the amount of energy spent against the air resistance was calculated assuming that the speed was constant from the start and equal to the average. However, since the mock trials were performed from a stationary start, in the initial phase of the race before a constant speed was attained the amount of the energy spent against the air resistance was in fact less than calculated. In a recent study by Olds et al. (18), the effects of the initial acceleration on the energy spent against the air resistance were estimated assuming that the final speed was attained after 100 m. Applying a similar approach to the present data, it can be shown that the overall energy requirement in our case was overestimated by 4.9%, 2.4%, 1%, and 0.5% for the four distances, respectively. Taking this factor into account would therefore reduce by an equal fraction the estimated performance times, thus bringing the $t_{act}/t_{theor}$ ratios of Table 4 to 1.028, 1.060, 1.066, and 1.075. Olds et al. (19) suggested that at the onset of the race the acceleration increases exponentially with a time constant of 10 s. Thus, in the present study and in the shortest distance (1.024 km, covered at the highest average speed of 1.7 m·s⁻¹), the athletes would have attained about 80% of the final speed by the end of the first 100 m. Therefore, any contribution of the residual acceleration would have barely affected the calculation of the overall metabolic power requirement. In any case, these examples show that a further improvement of the model could be achieved if the instantaneous speeds throughout the race, rather than the average ones, were considered.

Metabolic power requirement and body dimensions. Several investigators (3,24) have assumed implicitly that the area projected on the frontal plane (A) is a constant fraction of the body surface area (BS) of the subject, provided that the riding posture is the same. The constant $k'$ can therefore be normalized for BS, an easier quantity to determine than the actual values of the mechanical efficiency has only a minor effect on the theoretical times over the range of the studied speeds.
World records. Our approach allowed us also to calculate the theoretical best track cycling performances from a stationary start at sea level (Pb = 760 mm Hg and t = 20°C (273 K) air temperature) in calm air and to compare them with the world best performance times obtained on traditional racing bicycles. This was done applying the model to an "average" top level athlete of 75 kg BM, 175 cm stature with a net absolute MAP = 2.00 kW (corresponding to a gross $\dot{\text{VO}}_{2\text{max}} = 74 \text{ mL-min}^{-1}\cdot\text{kg}^{-1}$) and an overall AnS = 141.0 kJ (corresponding to 90 mL-O$_2$·kg$^{-1}$ in equivalent of oxygen). These values were reported for elite pursuit cyclists by Pyke et al. (27) and Medbo et al. (16) for MAP and AnS, respectively. We also assumed that this hypothetical top-level athlete would be able to sustain an aerobic power equivalent to the 90% of his MAP for 1 h. $E_c$ was calculated assuming that $k' = 0.72 \text{ J·m}^{-1}·\text{s}^2·m^{-2}$ and $C_{crr} = 15 \text{ J·m}^{-1}$ (for a total mass of 75 kg + 10 kg), as observed on average in the present study. The values of the theoretical times of performance are fairly close to the actual ones, even though the actual speeds are slightly underestimated ($t_{act}/t_{theor} = 0.977 \pm 0.019$) (Table 5).

**TABLE 5.** Actual and predicted best performance times for the indicated distances obtained by professional and amateur cyclists riding traditional racing bikes.

<table>
<thead>
<tr>
<th>Distance (km)</th>
<th>Best Performance (s)</th>
<th>Predicted (s)</th>
<th>Year</th>
<th>Athlete</th>
<th>Racing Track</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1:06.30</td>
<td>1:06.70</td>
<td>1980</td>
<td>U. Finster</td>
<td>Zurich, Switzerland</td>
</tr>
<tr>
<td>1.0</td>
<td>1:04.65</td>
<td>1:04.75</td>
<td>1980</td>
<td>L. Thomas</td>
<td>Moscow, Russia</td>
</tr>
<tr>
<td>4.0</td>
<td>2:37.69</td>
<td>2:38.15</td>
<td>1980</td>
<td>H. Wolf</td>
<td>Moscow, Russia</td>
</tr>
<tr>
<td>5.0</td>
<td>3:02.05</td>
<td>3:02.45</td>
<td>1980</td>
<td>H. Orsted</td>
<td>Copenhagen, Denmark</td>
</tr>
<tr>
<td>10.0</td>
<td>5:13.25</td>
<td>5:13.45</td>
<td>1980</td>
<td>A. Kranev</td>
<td>Moscow, Russia</td>
</tr>
<tr>
<td>10.0</td>
<td>5:12.66</td>
<td>5:12.65</td>
<td>1978</td>
<td>H. Orsted</td>
<td>Copenhagen, Denmark</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

The agreement between theoretical and actual performances emerging from the model is fairly good—almost comparable to the one obtained previously in running (25). This is remarkable since the predictive model was applied here to a form of locomotion in which the energy cost is strongly dependent on the speed. However, a 5% difference between actual and predicted times in elite athletes seems to make the model of somewhat limited use in predicting performance times for elite athletes. It seems also fair to point out that in this study the cyclists were not track
specialists and were always riding their standard road bicycles. Thus, the application of the present model to track cycling may be of limited value. However, the general validity of the model is independent of the cycling conditions, provided that the energy cost of cycling is experimentally assessed under the same conditions for which the theoretical best time of performance is estimated.

Finally, we would like to stress that the main value of the model does not reside in the possibility of predicting the exact time of performance on an individual basis. It rather resides in the possibility of quantifying the relative effect on the individual performances, of each physiological or biomechanical factor which explicitly appears in the model equations. Only a model wherein all variables have well defined physiological interpretations can allow this kind of analysis; an empirical model, no matter how good, could not be applied in this context.

In conclusion, the appropriate combination of the energetics of muscular exercise, on one side, with the energy cost of locomotion, on the other, does indeed allow one to predict individual performances with satisfactory accuracy. It therefore seems desirable to extend the approach described above to other forms of human or animal locomotion.

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REFERENCES


APPENDIX

This section is a detailed discussion of the theories and assumptions underlying the model applied in this study to calculate the theoretical best times of performance in track cycling.

We will first describe the dependency of the maximal metabolic power($E_{\text{max}}$) on the exhaustion time ($t_e$). We will then analyze the dependency of the rate of energy requirement in cycling($E_c$) on the time ($t_d$) necessary to cover a given distance ($d$). This will make it possible to obtain two equations: $E_{\text{max}} = F(t_e)$ and $E_c = F(t_d)$, from which it will become possible to calculate, for any given distance, the time ($t_e = t_d$) for which $E_{\text{max}} F(t_e) = E_c F(t_d)$. This will be assumed to yield the theoretical best performance time.

Maximal metabolic power. The maximal metabolic power($E_{\text{max}}$) is a decreasing function of the exhaustion time($t_e$).
If the metabolic power is maintained constant from the onset of the effort until exhaustion, the relationship between $E_{\text{max}}$ and $t_e$ is described by: equation [A1]

$$
\dot{E}_{\text{max}} = F \text{MAP} + \text{AnS} t_e^{-1} - F \text{MAP} \tau(1 - e^{-t_e \tau}) t_e^{-1}
$$

Equation 10A

In equation A1: 1) MAP is the maximal aerobic power, i.e., \(\cdot\text{VO}_2\text{max}\) above resting level expressed in kW; 2) F is the fraction of the net \(\cdot\text{VO}_2\text{max}\) sustained throughout the effort; 3) AnS is the maximal amount of energy derived from complete utilization of anaerobic (lactic and alactic) stores; and 4) [\(\tau\)] is the time constant with which \(\cdot\text{VO}_2\text{max}\) is attained at the onset of the effort. Equation A1 was derived by Wilkie from data obtained during exercise on cycle ergometer (31). The assumptions on which it is based were discussed by Wilkie (31) and di Prampero et al. (25). According to Wilkie, for $t_e$ between 45 s and 10 min, [\(\tau\)] = 10 s. However, this value, which was also used by di Prampero et al. (24), seems too low. In this paper we will therefore assume that [\(\tau\)] = 24 s, as shown by Binzoni et al. (1) for the rate of increase of \(\cdot\text{VO}_2\) at muscular level in humans.

Di Prampero et al. (25) assumed that for middle distance running $F = 1.0$ up to about 15 min. However, according to Péronet et al. (21) in elite endurance runners, for $t_e$ longer than 7 min, $F$ decreases as a linear function of the logarithm of $t_e$. Accordingly, we will assume that $F$ in equation 1 takes the following values: equation [A2] where $t_e$ is in seconds. Equations A1 and A2 make it possible to calculate $E_{\text{max}}$ as a function of $t_e$ for any given subject whose \(\cdot\text{VO}_2\text{max}\) and AnS are known. This was done in Figure 1A where $E_{\text{max}}$ is represented as a function of $t_e$ for a theoretical elite athlete (75 kg body mass), assuming MAP = 1.80 kW (corresponding to a \(\cdot\text{VO}_2\text{max}\) above resting of 69 mL O\(_2\)·min\(^{-1}\)·kg\(^{-1}\)) and AnS = 106.6 kJ (68 mL O\(_2\)·kg\(^{-1}\)).

Equation 10B

\[
F\begin{cases} 
1.00; & \text{for } 45 \text{ s} < t_e < 420 \text{ s} \\
1 - 0.0568 \ln(t_e/420); & \text{for } t_e > 420 \text{ s}
\end{cases}
\]

Figure 1A: Metabolic power requirement (Ec, kW) in track cycling is indicated as a function of the time necessary to cover the distance of 1.0 km. Maximal metabolic power (Emax, kW) of a top athlete is also indicated on the same time axis. Best performance time is indicated by the abscissa value at which the two functions cross.

In this study AnS was calculated from the sum of the amount of energy derived from: a) the splitting of high energy phosphates in the working muscles; and b) the anaerobic glycolysis through the production of lactate. The former was assumed to be equal to that reported by di Prampero (22) and corrected as a function of age according to Cerretelli et al. (5): it amounted on the average to 19.6 mL O\(_2\)·kg\(^{-1}\) of body mass. The lactic component of AnS (mL O\(_2\)·kg\(^{-1}\) of body mass) was calculated from the peak [\(\text{La}\)] (above resting) measured after the maximal trials, on the basis of an energetic equivalent for lactate of 62.7 J·kg\(^{-1}\) of body mass per net increase of blood [\(\text{La}\)] (22).

Rate of energy expenditure in track cycling. As described by others (3,24,26) and observed also in this study, the energy cost per unit of distance during constant speed cycling on flat terrain ($C_C$) increases with the square of the air speed ($v$): equation [A3] where $C_{\text{cr}}$ is the nonaerodynamic component of the cost of cycling and the second term is the energy spent per unit distance against air resistance with $k'$ as a constant. In turn, $C_{\text{cr}}$ results from energy losses between the rotating parts of the transmission chain and between the tires and the terrain.

Equation 10C

Cycling competitions are generally performed from a stationary start. In this case, the overall energy cost must include also the energy spent per unit distance ($C_{\text{cin}}$) to accelerate the body and the bicycle from zero to the final ground speed ($s$): equation [A4] where $M$ is the overall moving mass, $d$ the distance covered and where the value of the overall efficiency of cycling ([\(\eta\)]) was introduced to convert the external work into its metabolic equivalent. Therefore,
the overall energy cost of cycling($C_{ctot}$) is given by the sum of equations A3 and A4: equation [A5] in equations A5, wind speed ($v$) and ground speed ($s$) are indicated separately; it goes without saying, however, that in still air $v = s$.

**Equation 10E**

The rate of energy expenditure per unit of time is given by the product of the overall energy cost per unit distance times the ground speed. Furthermore, in any given competition, the distance ($d$) is constant and known, so that the ground speed can be replaced by the ratio $d/t_2$, where $t_2$ is the time to cover the distance at stake. Assuming further that the wind speed is nil ($s = v = d/t_2$), the rate of energy expenditure per unit of time can be obtained from equation A4: equation [A6] Equation A6 makes it possible to calculate the rate of energy expenditure in cycling from a stationary start over any given distance covered in a given time($t_2$), provided that the quantities $C_{ctot}$, $k'$, $M$, and $[\eta]$ are known. $E_c$ is reported in Figure A1 for a cyclist of 75 kg body mass and 175 cm stature (body surface = 1.90 m$^2$) covering a distance of 1.0 km in a time ranging from 90 to 50 s for $C_{ctot} = 15$ J·m$^{-1}$, $k' = 0.77$ J·s$^2$·m$^{-3}$ (22) and $[\eta] = 0.22$, as from current literature (26).

**Equation 10F**

Best performance. As shown above (see also Fig. A1): 1) the metabolic power requirement for covering any given distance($E_c$) is a decreasing function of the time of performance($t_2$) (equation A6), and 2) the maximal metabolic power ($E_{\text{max}}$) that a given subject can sustain at constant level is a decreasing function of the time of exhaustion($t_e$) (equation A1). Figure A1 shows that for a certain range of $t$ values, $E_{\text{max}}$ is below the function describing the metabolic power requirement ($E_c$). These times will therefore be unattainable by the specific subject. For longer $t$ values, $E_{\text{max}}$ is above$E_c$; hence the hypothetical cyclist could have covered the distance in a shorter time. The time of best performance will be given by the abscissa at which the two functions cross. In practice, the time value solving the equalities $E_{\text{max}}(t_e) = E_c(t_2)$; i.e., the time value for which the two functions of the figure cross can be obtained either graphically or by means of a computerized iterative procedure on the basis of the known value of $C_{ctot}$, $k'$, $\text{VO}_2\text{max}$, $A\text{inS}$, and $F$.

Air resistance and environmental conditions. As mentioned in the methods section, the constant $k'$ is proportional to the air density($[\rho]$), to the area projected on the frontal plane by the mobile object ($A$), to the dimensionless drag coefficient ($C_d$) and to the reciprocal of the mechanical efficiency ($[\eta]$) of the locomotion (see equation 8). In turn, the air density is directly proportional to the barometric pressure ($P_b$, mm Hg) and inversely proportional to the absolute temperature ($T$, K) (equation 10). Equations 8 and 10 in the methods section can be used easily to calculate $k'$ for any given subject and for the same cycling posture, provided that $P_b$ and $T$ are known. Indeed, under these conditions: equation [A7] Therefore, since the area projected on the frontal plane ($A$), the cycling efficiency ($[\eta]$), and the drag coefficient are identical, the following equalities must apply: equation [A8] where $[\rho]_1$ and $[\rho]_2$ are the air densities applying in the two conditions. Rearranging equation 8A and since the air density depends on the barometric pressure and the temperature of the air, one obtains: equation [A9]

**Equation 10G**

**Equation 10H**

**Equation 10I**

Therefore, if $k'_1$ is known, and if $P_b$ and $T$ are measured in both conditions, the value of $k'_2$ value applying to any new environmental condition can be readily calculated. This makes it possible to correct the effects of the environmental conditions on the metabolic power (see equation A6).

Relative humidity, and hence water vapor pressure, was not measured either during the tests for assessing $C_d$ or during the mock trials. Since in this study the air density ($[\rho]$) refers to dry conditions, the impact of this simplification on the calculation of $k'$ and $C_d$ needs to be addressed briefly. To fulfil this purpose, $C_d$ was calculated for each cyclist using the values of $[\rho]$ for dry and wet air, simulating for wet conditions different values of the relative humidity ranging from 90 to 10%. The air density of wet air could be calculated as described in the CRC Handbook of Physics and
Chemistry (6). These calculations show that the average values of $k'$ and $C_d$ obtained after the correction for air density prevailing in wet conditions are not significantly different from those obtained assuming dry air (equations 9 and A9).

Key Words: $\cdot$VO$_{2\text{max}}$; ANAEROBIC CAPACITY; MUSCULAR EXERCISE; MAXIMAL POWER; WORLD RECORDS; MODELING IN PHYSIOLOGY