Energetics of best performances in middle-distance running

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DI PRAMPERO, P. E., C. CAPELLI, P. PAGLIARO, G. ANTONUTTO, M. GIRARDIS, P. ZAMPARO, AND R. G. SOULE. *Energetics of best performances in middle-distance running.* J. Appl. Physiol. 74(5): 2318-2324, 1993.—Oxygen consumption ($\dot{V}O_2$) and blood lactate concentration were determined during constant-speed track running on 16 runners of intermediate level competing in middle distances (0.8–5.0 km). The energy cost of track running per unit distance (C_r) was then obtained from the ratio of steady-state $\dot{V}O_2$, corrected for lactate production, to speed; it was found to be independent of speed, its overall mean being $3.72 \pm 0.24\ J \cdot kg^{-1} \cdot m^{-1}$ (n = 58; 1 ml O_2 = 20.9 J). Maximal $\dot{V}O_2$ ($\dot{V}O_{2\,max}$) was also measured on the same subjects. Theoretical record times were then calculated for each distance and subject and compared with actual seasonal best performances as follows. The maximal metabolic power ($\dot{E}_{r\,max}$) a subject can maintain in running is a known function of $\dot{V}O_{2\,max}$ and maximal anaerobic capacity and of the effort duration to exhaustion (t_e). $\dot{E}_{r\,max}$ was then calculated as a function of t_e from $\dot{V}O_{2\,max}$, assuming a standard value for maximal anaerobic capacity. The metabolic power requirement ($\dot{E}_r$) necessary to cover a given distance (d) was calculated as a function of performance time (t) from the product $C_r dt^{-1} = \dot{E}_r$. The time values that solve the equality $\dot{E}_{r\,max}(t_e) = \dot{E}_r(t)$, assumed to yield the theoretical best t, were obtained by an iterative procedure for any given subject and distance and compared with actual records. These calculations, applied to our data and to similar data obtained by Lacour et al. (*Eur. J. Appl. Physiol. Occup. Physiol.* 60: 38-43, 1990) on French elite athletes, show good agreement between actual and calculated best t values; their ratio was 1.078 ± 0.095 (n = 41) and 1.026 ± 0.0042 (n = 68), respectively, over distances from 800 to 5,000 m.

energy cost of running; maximal power; world records

THE ENERGETICS OF RUNNING can be appropriately described provided that its energy cost (C_r) is known. C_r is defined as the energy required above resting to transport the subject's body over one unit of distance. Throughout this paper it is expressed in joules per meter on the assumption that 1 ml O_2 consumed in the human body yields 20.9 J (which is strictly true only if the respiratory quotient = 0.96). The metabolic power above resting ($\dot{E}_r$) for proceeding at speed v is given by

$$\dot{E}_r = C_r v \tag{1}$$

where, if C_r is expressed in joules per kilogram per meter and v in meters per second, $\dot{E}_r$ in turn is obtained in watts per kilogram. Rearranging *Eq. 1* and applying it to maximal conditions

$$v_{max} = \dot{E}_{r\,max} C_r^{-1} \tag{2}$$

it can be easily shown that the maximal speed (v_{max}) depends both on the maximal metabolic power ($\dot{E}_{r\,max}$) of the subject and on C_r at that v. *Equation 2* applies regardless of the sources (aerobic or anaerobic) supplying the energy for work performance, the only constraint being that $\dot{E}_r$ from different sources must be expressed in appropriate units.

In aerobic conditions, $\dot{E}_{r\,max}$ is set essentially by maximal oxygen consumption ($\dot{V}O_{2\,max}$). However, because $\dot{V}O_{2\,max}$ cannot be indefinitely maintained, for prolonged exercise *Eq. 2* becomes

$$v_{end} = F\alpha \dot{V}O_{2\,max} C_r^{-1} \tag{3}$$

where v_{end} is the endurance speed, F is the maximal fraction of $\dot{V}O_{2\,max}$ that can be sustained throughout the entire effort duration, and α is the factor expressing O_2 consumption ($\dot{V}O_2$) as $\dot{E}_r$ (1 ml/min = 0.35 W, which is strictly true when respiratory quotient = 0.96). The relationship between v predicted from *Eq. 3* and the actual average v over a marathon or half-marathon (21 km) on 36 subjects turned out to be rather good. Indeed the corresponding r^2 amounted to 0.72, and the average ratio of the actual speed to v_{end} was not significantly different from 1, amounting to 0.978 ± 0.079 (2, 12).

The aim of the present paper was to assess whether a similar approach could be utilized to also predict individual v_{max} values for shorter running distances (800–5,000 m).

THEORY

Equation 2 shows that the theoretical v_{max} is set by the ratio of $\dot{E}_{r\,max}$ to C_r. However, because of the contribution of the anaerobic stores to the overall metabolic power, which is larger the shorter the time of performance (t), $\dot{E}_{r\,max}$ decreases according to an approximately hyperbolic function of the exhaustion time (t_e) (18). As a consequence, *Eq. 2* cannot be directly used to predict v_{max} without prior knowledge of t, an obviously circular requirement. We circumvent this drawback as follows.

The relationship between maximal external power in cycling ($\dot{W}_{max}$; in kW) and effort t_e (in s) can be described by (19)

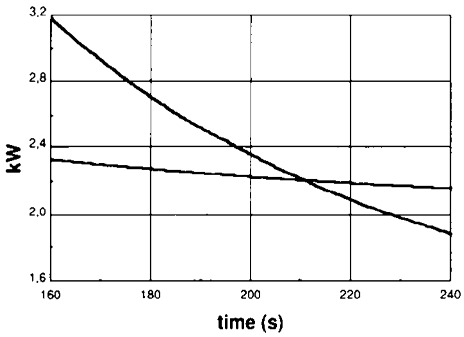

FIG. 1. Metabolic power requirement ($\dot{E}_r$) in track running to cover 1,500 m as a function of time is indicated (*top curve*). Maximal available metabolic power of a top athlete ($\dot{E}_{r\,max}$) is also indicated on same time axis (*bottom curve*) (for details see text).

$$\dot{W}_{max} = At_e^{-1} + B - Bk^{-1}(1 - e^{-kt_e})t_e^{-1} \quad (4)$$

where A is the amount of mechanical work that can be derived from complete utilization of the anaerobic (alactic + lactic) sources, B is the mechanical power sustainable on the basis of $\dot{V}O_{2\,max}$ alone, and $k = 0.1\ s^{-1}$ is the velocity constant with which $\dot{V}O_{2\,max}$ is attained at the onset of exercise. The constant B depends obviously on the subject's $\dot{V}O_{2\,max}$. The third term of *Eq. 4* is due to the fact that $\dot{V}O_{2\,max}$ cannot be instantaneously reached at the onset of work. It can be calculated that, for the values of A and B observed in athletes, the weight of the third term decreases with increasing t_e from ~11% of $\dot{W}_{max}$ for t_e = 40 s to 1.5% for t_e = 10 min.

On the basis of the above analysis, it seems reasonable to describe the relationship between $\dot{E}_{r\,max}$ and t_e in similar terms

$$\dot{E}_{r\,max} = \mathrm{AnS}t_e^{-1} + \mathrm{MAP} - \mathrm{MAP}k^{-1}(1 - e^{-kt_e})t_e^{-1} \quad (5)$$

where AnS is the maximal amount of energy released by anaerobic (lactic + alactic) sources and MAP is the subject's maximal aerobic power. Thus, *Eq. 5* allows calculation of the $\dot{E}_{r\,max}$ on which the subject can rely as a function of t_e, provided that the subject's AnS and MAP are known.

The $\dot{E}_r$ for running at speed v is given by the product $C_r v$ (see *Eq. 1*). Hence, setting $v = dt^{-1}$

$$\dot{E}_r = C_r dt^{-1} \quad (1a)$$

and because for any given event in track running distance (d) is obviously constant and known, $\dot{E}_r$ can be calculated as a function of the t employed to cover the distance in question, provided that C_r is known. In Fig. 1, the $\dot{E}_r$ value for covering the 1,500-m distance in 160–240 s on the basis of a C_r value equal to the average reported in the literature ($3.86\ J \cdot kg^{-1} \cdot m^{-1}$; Ref. 10) and corrected to take into account the energy spent against the air resistance and to accelerate the body from zero to the final speed (*Eq. 8*) is plotted as a function of the time taken to cover the specified distance. We also report $\dot{E}_{r\,max}$, as obtained from *Eq. 5* on the basis of the values of MAP and AnS presumed to apply to an hypothetical elite athlete (25.78 W/kg and 1.42 kJ/kg, corresponding, in O_2 equivalents, to $\dot{V}O_{2\,max}$ of 74.0 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$ above resting and to 68.0 ml O_2/kg, respectively) (7). Figure 1 shows that, for a certain range of t values, $\dot{E}_{r\,max}$ is below the function describing $\dot{E}_r$. These t values will therefore be unattainable by the subject in question. For longer t values, $\dot{E}_{r\,max}$ is above $\dot{E}_r$; hence the subject could have covered the distance in a shorter time. The subject's predicted best time is obviously given by the abscissa value at which the two functions cross.

In the present study, individual predicted best times over a given distance will be obtained from the relationship between $\dot{E}_{r\,max}$ and t_e described by *Eq. 5*, on the one hand, and $\dot{E}_r$ and t described by *Eq. 1a*, on the other hand. In practice, the t values solving the equality $\dot{E}_{r\,max}(t_e) = Er(t)$, i.e., the t values at which the 2 functions of Fig. 1 cross, will be calculated by means of a computerized iterative procedure on the basis of the values of C_r and $\dot{V}O_{2\,max}$ experimentally determined on a group of intermediate level runners and assuming AnS as determined by Cerretelli et al. (5). The obtained t values over distances from 800 to 5,000 m, assumed to yield the best t values, are compared with the actual seasonal records over the same distances. This set of calculations is repeated on the data reported by Lacour et al. (15) for French elite runners on whom these authors assessed C_r and $\dot{V}O_{2\,max}$ for level treadmill running and for whom the individual record times over 800, 1,500, 3,000, and 5,000 m, for the same season during which $\dot{V}O_{2\,max}$ and C_r were obtained, are also reported.

METHODS AND EXPERIMENTAL PROCEDURE

The experiments were performed on 16 subjects whose anthropometric and physiological characteristics are reported in Table 1.

The subjects' $\dot{V}O_{2\,max}$ was determined by the standard open circuit method during an incremental treadmill running test. The treadmill was inclined 1.7° to the horizontal, and, after 5 min at 10 km/h, the speed was increased by 2 km/h every 4 min until volitional exhaustion. In the last 30 s of each constant-load period the expired air was collected in a 100-liter Douglas bag. The collection time was measured by stop watch, and expired air volume and composition were determined by means of a dry gas meter (MC-6, S. I. M. Brunt) and a previously calibrated paramagnetic O_2 (Oxynos 1-C, Leybold Heraeus) and infrared CO_2 analyzer (Binos 1, Leybold Heraeus). Heart frequency was measured by means of a cardiometer (Baumann Recorder, Baumann CEM) on a 15-s basis. The highest measured $\dot{V}O_2$ value was assumed to represent $\dot{V}O_{2\,max}$ when the heart rate was equal to or greater than the age-predicted maximum and the venous blood lactate concentration ($[La]_b$) was >8.0 mM. On a subset of subjects, i.e., on *subjects 13, 14, 15,* and *16*, $\dot{V}O_{2\,max}$ was determined during an incremental cycloergometric test as follows. After 4 min at 30 W, the power was increased by 30 W every 3 min until volitional exhaustion. $\dot{V}O_2$, carbon dioxide production (STPD), and minute ventilation (BTPS) were calculated by means of mass spectrometer (model 2200, Airspec) using an argon dilution technique (6). The highest measured $\dot{V}O_2$ value was assumed to represent $\dot{V}O_{2\,max}$ when *1*) the heart rate was equal to or greater than the age-predicted maximum; *2*) a leveling off of $\dot{V}O_2$ took place, i.e., $\dot{V}O_2$ increased by <100 ml/min above the level measured during the previous work load (30 W lower) compared with an expected in-

TABLE 1. *Anthropometric characteristics, $\dot{V}O_{2\,max}$, Cr, $\Delta[La]_b$, and Cr_{La}, for all subjects*

Subj No.	Sex	Age, yr	Body Mass, kg	Height, cm	$\dot{V}O_{2\,max}$, $ml \cdot min^{-1} \cdot kg^{-1}$	v, m/s	C_r, $J \cdot m^{-1} \cdot kg^{-1}$	$\Delta[La]_b$, mM	$C_{r,La}$ $J \cdot m^{-1} \cdot kg^{-1}$	$C_{r,La}$ %
1	F	16	50.4	169.0	49.5	3.66	3.62	4.62	0.242	6.68
						3.88	3.56	3.05	0.159	4.46
						4.10	3.65	5.84	0.295	8.08
						4.35	3.69	12.72	0.665	18.02
2	F	16	52.5	165.0	47.0	3.69	3.80	4.30	0.225	5.92
						3.92	4.01	7.06	0.370	9.22
						4.17	3.92	8.59	0.449	11.45
						4.44	3.98	11.61	0.601	15.10
3	F	16	51.1	160.0	49.5	3.82	3.78	1.19	0.063	1.67
						4.07	4.12	4.31	0.225	5.46
						4.32	4.02	5.77	0.301	7.48
						4.56	3.88	5.87	0.307	7.91
4	F	16	45.0	170.0	39.0	3.83	3.70	5.43	0.271	7.32
						4.15	3.45	6.12	0.319	9.25
						4.18	3.48	6.37	0.319	9.17
						4.55	3.43	10.59	0.554	16.15
5	M	16	70.0	175.0	54.1	4.33	3.48	1.82	0.096	2.76
						4.35	3.65	2.79	0.146	4.00
						4.71	3.25	4.58	0.240	7.38
						5.19	3.41	10.63	0.555	16.27
6	M	16	62.7	174.0	60.3	4.67	3.92	1.95	0.102	2.60
						4.96	3.61	4.18	0.219	6.07
						5.24	3.46	7.67	0.401	11.58
						5.56	3.82	9.16	0.479	12.53
7	F	16	58.1	174.5	43.2	4.05	3.52	4.20	0.219	6.22
						4.33	3.50	6.69	0.349	9.97
						4.55	3.59	11.52	0.602	16.78
						4.80	3.13	8.25	0.424	13.55
8	F	19	51.0	169.5	53.7	4.17	3.60	2.39	0.119	3.30
						4.52	3.96	8.14	0.389	9.82
						4.75	3.85	9.10	0.456	11.80
						4.84	3.77	8.82	0.462	12.25
9	M	16	75.0	177.0	58.8	4.29	3.81	2.50	0.132	3.46
						4.58	3.81	4.97	0.259	6.79
						4.86	3.56	5.99	0.313	8.79
10	M	19	63.0	191.0	62.4	4.92	3.82	4.89	0.255	6.67
						5.24	3.68	3.11	0.163	4.42
						5.53	3.86	6.73	0.351	9.09
						5.91	3.40	7.18	0.376	11.06
11	M	19	54.0	168.0	60.2	5.04	3.65	5.15	0.259	7.09
						5.30	3.96	6.39	0.319	8.05
						5.58	3.80	7.45	0.374	9.84
						6.00	4.03	14.43	0.754	18.70
12	M	19	62.5	180.0	60.6	5.16	3.62	5.23	0.263	7.26
						5.30	3.76	5.27	0.263	6.99
						5.66	3.77	7.86	0.411	10.90
						5.88	3.54	10.83	0.566	15.90
13	M	24	64.2	173.5	65.6	4.35	3.72			
						4.78	3.91			
14	M	22	70.8	182.0	62.5	4.25	3.89			
						4.53	3.90			
						5.19	4.06			
15	M	20	68.5	181.0	58.8	4.15	3.36			
						4.46	3.89			
						4.90	3.93	2.30	0.140	3.56
						5.15	3.84	3.60	0.230	5.99
16	M	22	61.9	172.0	58.7	4.49	3.26			
						5.02	4.37	2.60	0.150	3.43
			Mean ± SD				3.72±0.238			

n = 58 measurements. $\dot{V}O_{2\,max}$, maximal O_2 consumption; v, speed; C_r, energy cost of running; $\Delta[La]_b$, net lactate accumulation in venous blood; $C_{r,La}$, lactate contribution to overall energy cost. See text for details.

crease of ~360 ml/min; and *3*) the respiratory exchange ratio was ≥1.00.

The C_r on a standard 400-m tartan track was determined as follows. The subjects ran at constant speed set by acoustic signals (Balise Temporelle, Baumann CEM) with a predetermined frequency so that at each signal, if running at the appropriate speed, the subject was passing in front of equally spaced (20 m) visual marks. Each subject ran at two to four speeds (see Table 1) ~1 km/h apart in increasing order. The highest speed was set so as to correspond to the maximum the subject could maintain over a distance of 2,000 m, as judged from previous best performance for that season.

Expired air was collected, by means of standard lightweight respiratory valves and hoses (4.0 cm ID), in a 50-liter rubber bag held by an operator riding a bicycle at the side of the runner. A three-way valve operating a stopwatch allowed the expired air to be either exhaled freely or collected in the bag for a known period of time. At each speed the expired air collection was initiated after ~4 min, at which time a vocal signal imparted by the experimenter informed the subject that he had to turn the three-way valve. When the bag was full, at a second vocal signal the subject terminated the air collection by operating the three-way valve again, and the running period was over. Collection times ranged from 28 to 70 s. This procedure permitted determination of steady-state $\dot{V}O_2$ by the same standard open-circuit procedure described above for the assessment of $\dot{V}O_{2\,max}$ during treadmill running. The heart rate during constant-speed steady-state running was also determined by a cardiometer (Baumann Recorder, Baumann CEM). $[La]_b$ drawn from the antecubital vein was determined by an enzymatic method (13) at the 4th and 6th min after each run.

When $[La]_b$ was negligible (<2.0 mM), C_r was calculated from the ratio of the steady-state $\dot{V}O_2$ above resting to the running speed. This ratio was then expressed in joules per kilogram per meter on the basis of an energetic equivalent of 20.9 J/l O_2. When $[La]_b$ exceeded the above threshold, its contribution to C_r was calculated as follows. The net increase of $[La]_b$ ($\Delta[La]_b$) was obtained subtracting the preexercise value from the peak attained in the recovery. The energetic value of $\Delta[La]_b$ was then calculated on the basis of an equivalent of 60 $J \cdot kg^{-1} \cdot mM^{-1}$ (3 ml $O_2 \cdot kg^{-1} \cdot mM^{-1}$) (7). Finally, the overall C_r above resting was determined by dividing the energetic value of $\Delta[La]_b$ by the overall distance covered and adding it to the aerobic energy cost obtained as described above.

RESULTS

The values of C_r inclusive of the lactic contribution ($C_{r,La}$) are reported in Table 1 for all subjects at all speeds, together with the individual values of $\dot{V}O_{2\,max}$ and the increase in $[La]_b$ as a result of the run. The last two columns in Table 1 report the increase of $[La]_b$ expressed either in equivalent $\dot{V}O_2$ divided by the distance covered (in $J \cdot kg^{-1} \cdot m^{-1}$) or in percentage of the overall energy cost of running (in %). $C_{r,La}$ increased from 5.08 ± 2.13% (n = 12) at the lowest speed to 12.55 ± 4.62% (n = 14) at the highest speed.

C_r was found to be essentially independent of the speed, at least in the investigated range (Fig. 2); its overall mean was 3.72 ± 0.238 (SD) $J \cdot kg^{-1} \cdot m^{-1}$. This value is close to those previously reported by others in this same speed range [3.65 ± 0.286 $J \cdot kg^{-1} \cdot m^{-1}$ (2); 3.57–3.84 $J \cdot kg^{-1} \cdot m^{-1}$ (3); 3.78 ± 0.117 $J \cdot kg^{-1} \cdot m^{-1}$ (15)].

DISCUSSION

$\dot{V}O_{2\,max}$. The values of $\dot{V}O_{2\,max}$ determined in this study were on average 60.2 ± 3.0 $ml \cdot kg^{-1} \cdot min^{-1}$ for the males

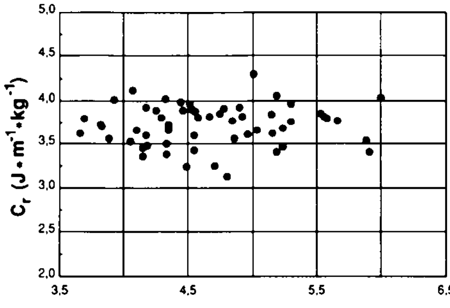

FIG. 2. Overall energy cost of running above resting (C_r) as function of running speed in all subjects.

and 50.0 ± 5.2 $ml \cdot kg^{-1} \cdot min^{-1}$ for the females. In view of their average age (19.3 ± 2.8 and 16.6 ± 1.3 yr, respectively), our subjects can therefore be considered as intermediate level athletes. In four subjects, $\dot{V}O_{2\,max}$ could not be determined on the treadmill; their values reported in Table 1 were obtained on the bicycle ergometer, which allegedly yields values 4–8% lower than those obtained on the treadmill (1). However, $\dot{V}O_2$ values determined on these same subjects at the highest speed they could maintain over 2,000 m were not significantly different than those obtained on the bicycle and reported in Table 1 (mean of paired differences = 0.70 ± 5.9 $ml \cdot kg^{-1} \cdot min^{-1}$, n = 4; the large SD value resulted from the small number of paired data).

Maximal theoretical performances. In this study C_r was determined for running at constant speed. However, because maximal performances in track running are generally performed from a stationary start, the overall energy cost, inclusive of the energy spent to accelerate the body from zero to final speed ($C_{r,tot}$, $J \cdot m^{-1} \cdot kg^{-1}$), is given by

$$C_{r,tot} = C_r + (0.5Mv^2\eta^{-1}d^{-1})M^{-1} \qquad (6)$$

where M is the mass of the subject and η is the efficiency of transformation of metabolic energy into kinetic energy. The latter can be assumed to be 0.25, since in the initial acceleration phase no recovery of elastic energy can take place and hence the overall running efficiency must approach the efficiency of muscular contraction (4). If η is assumed to be equal to 0.25, *Eq. 6* reduces to

$$C_{r,tot} = C_r + 2v^2d^{-1} \qquad (7)$$

It can be calculated from *Eq. 7* that, over the shorter distances and faster speeds, the kinetic energy term leads to substantial increases of C_r. Indeed, for the 100-m run, at speeds close to the world record (10 m/s), it amounts to 4 $J \cdot m^{-1} \cdot kg^{-1}$, thus essentially doubling the overall value of C_r. However, for longer distances and slower speeds, as was the case in the present study, the kinetic energy term becomes much smaller, i.e., at world record speed it amounts to only 10 and 1% of the total for the 800- and 5,000-m runs, respectively.

The obtained $C_{r,tot}$ values were used in *Eq. 1a* (setting $v = dt^{-1}$) to calculate the relationship between $\dot{E}_r$ and t_e for any given d. $\dot{E}_{r\,max}$ was than calculated from *Eq. 5* on the basis of the individual $\dot{V}O_{2\,max}$ values and estimating AnS as follows. It was assumed that, for a 25-yr-old adult athletic male, AnS = 1.43 kJ/kg (68.0 ml O_2/kg) (7) and that, as reported by Cerretelli et al. (5), for younger sub-

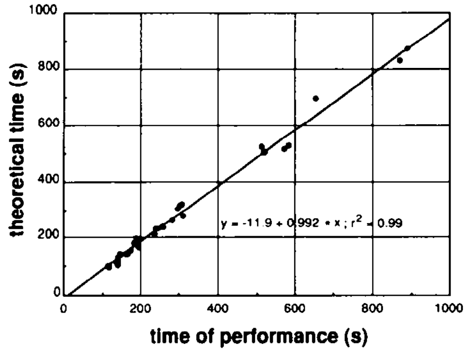

FIG. 3. Calculated record times as function of seasonal records for each subject of present study.

jects AnS was smaller, amounting on average to 83% of the above at age 16 yr and to 94% at age 19 yr. Thus, for any given distance, both $\dot{E}_r$ and $\dot{E}_{r\,max}$ were calculated as a function of time (t_e for $\dot{E}_{r\,max}$ and t for $\dot{E}_r$). The time value for which $\dot{E}_{r\,max} = \dot{E}_r$, assumed to yield the theoretical record time over the distance in question, was then obtained as described above (see THEORY). It was found to be essentially equal to the individual records determined on the same subjects (Fig. 3).

The same set of calculations was applied to the data reported by Lacour et al. (15) for French elite runners on whom these authors assessed the C_r and $\dot{V}O_{2\,max}$ of level treadmill running. The latter value, together with an assumed value of 1.43 kJ/kg for the anaerobic energy stores (AnS) (7), allowed calculation of $\dot{E}_{r\,max}$ as a function of the t_e. (No age correction was applied to AnS in this case, since the average age was 24 yr.) Because in this case C_r was determined during constant-speed treadmill running, it was corrected also for the energy spent against air resistance

$$C_{r,tot} = C_{r,na} + k'v^2 + 2v^2d^{-1} \qquad (8)$$

where $C_{r,na}$ is the cost per unit distance against nonaerodynamic forces as determined by Lacour et al. (15) and k' is the proportionality constant between cost against air resistance and air speed squared (assumed from current literature to be 0.01 $J \cdot s^2 \cdot m^{-3} \cdot kg$ body mass^{-1}) (17).

The theoretical best performances could then be calculated as described above and were found to be essentially equal to the individual records (Fig. 4).

Statistical analysis. The goodness of fit of the model was evaluated from two indexes: the ratios of the actual (t_{act}) to calculated performance times (t_{calc}) and the error term between t_{act} and t_{calc} (t_{err}), which was obtained by

$$t_{err}\,(\%) = \sum_{i=1}^{n} \frac{100}{n} \left(\left| t_{act} - t_{calc} \right| \right)_i / t_{act} \qquad (9)$$

where n is the number of observations for each d. The two indexes, referring to the present data and to those by Lacour et al. (15), are reported in Table 2, which shows that the agreement between t_{act} and t_{calc} is fairly good. The only exception concerns the shorter distances (800 and 1,000 m) for which t_{calc} is shorter (and hence the average speeds greater) than t_{act}.

World records. The approach described also allowed calculation of the theoretical world records for a hypothetical elite athlete and comparison of them with the 1989 world records for 800- to 5,000-m track running. This was done by *1*) assuming $C_{r,na} = 3.79\ J \cdot m^{-1} \cdot kg^{-1}$, as reported by Lacour et al. (15) for elite athletes, and $k' = 0.72\ J \cdot s^2 \cdot m^{-3}$ for a subject of 70 kg body mass and 175 cm height, as from Pugh's (17) data; and *2*) inserting into *Eq. 5* the values applicable to an "average" elite athlete: AnS = 1.43 kJ/kg (68 ml O_2/kg) and MAP = 25.7 W/kg (corresponding to a $\dot{V}O_{2\,max}$ of 74 $ml \cdot kg^{-1} \cdot min^{-1}$ above resting) (7). The values for t are very close to the 1989 world records for distances from 800 to 5,000 m (Table 3).

General discussion. In the present study, best individual performances in running were obtained from the known relationships between $\dot{E}_{r\,max}$ and t_e, on the one hand, and $\dot{E}_r$ and t over a given distance, on the other

TABLE 2. *t_{err} and t_{act}/t_{calc} values for present study and data of Lacour et al. (15)*

Distance, km	n	% t_{err}	t_{act}/t_{calc}
		Present study	
0.8	12	13.78 (6.7–25.9)	1.160±0.093*
1.0	8	7.46 (1.32–11.6)	1.065±0.091
1.5	11	5.93 (0.02–10.6)	1.038±0.064
3.0	7	5.30 (1.91–10.2)	1.026±0.066
5.0	3	2.44 (0.59–4.70)	1.025±0.022
Overall mean ± SD			1.078±0.095*
		Data from Lacour et al.	
0.8	13	6.91 (1.69–11.56)	1.075±0.0334*
1.5	24	2.26 (0.61–5.49)	1.016±0.0250†
3.0	18	2.29 (0.72–6.02)	1.015±0.0274
5.0	18	3.02 (0.52–11.7)	1.106±0.0240
Overall mean ± SD			1.026±0.0042*

Values are means or means ± SD, with ranges given in parentheses; n, no. of subjects. t_{err}, error between actual and calculated best performance times (see *Eq. 9*); t_{act}/t_{calc}, ratio of actual to calculated best performance times. t_{act} refers to best seasonal performance for each subject. For t_{act} values referring to data of Lacour et al., see Ref. 15. Significant difference based on Student's t test (H∅ = 1; Ha ≠ 1): * $P < 0.001$; † $P < 0.05$.

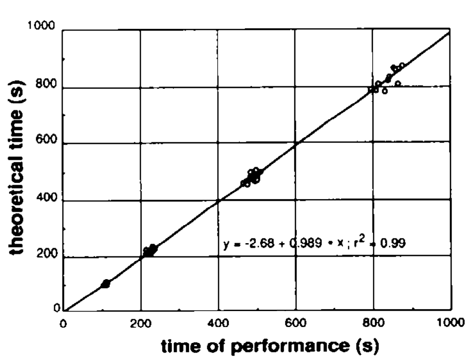

FIG. 4. Calculated record times as function of actual times of performance calculated from data of Lacour et al. (15).

TABLE 3. *World records for 1989 and predicted record times for indicated distances*

Distance, km	World Records (1989), s	World Records Predicted, s	Ratio of Actual to Predicted Records
0.8	101.73 (1:41:73)	98.76	1.030
1.0	132.18 (2:12:18)	130.23	1.015
1.5	209.46 (3:29.46)	210.12	1.003
3.0	452.10 (7:32.10)	451.94	0.999
5.0	778.39 (12:58.39)	776.38	1.003

Values in parentheses are given in minutes. Predicted records were calculated assuming a maximal aerobic power of 1.8 kW (corresponding to $\dot{V}O_{2\,max}$ of 74 ml·kg^{-1}·min^{-1} above resting) and a maximal anaerobic capacity of 100 kJ (68 ml O_2/kg) in a 70-kg, 175-cm elite athlete. For further details see text.

hand. The time values that solve the equalities $\dot{E}_{r\,max} \times (t_e) = \dot{E}_r(t)$ were then obtained and assumed to yield the theoretical best t for a given subject over a given distance.

$\dot{E}_{r\,max}$ was obtained from the relationship between maximal mechanical power in cycling and t_e (*Eq. 5*) established by setting the power output at a constant level and pedalling until exhaustion (19). Even though this strategy may not be appropriate for winning a race, it does seem to be the best to set a record. Indeed, it has been shown on theoretical grounds (14) that to establish a record performance in running, *1*) the power output must be constant throughout and maximal given the duration of the effort, which obviously implies that *2*) t must coincide with t_e. The values of t, as calculated in this study, meet the above requirements. Hence it seems legitimate to assume them to be the theoretical individual best performances.

It goes without saying that the validity of the predictions depends on the accuracy with which $\dot{E}_{r\,max}$ and $\dot{E}_r$ can be assessed. In turn, $\dot{E}_{r\,max}$ depends on the maximal AnS and MAP (see *Eq. 5*), and $\dot{E}_r$ depends on C_r (*Eq. 1a*). The calculations reported in Table 4 show that a 5% change in the estimated AnS leads to a difference in the predicted performance, decreasing from 1.8 to 0.3% as the distance is increased from 800 to 5,000 m. On the contrary, the effect of a 5% change in MAP ($\dot{V}O_{2\,max}$) is larger and increases with the distance from 2.7% for 800 m to 3.9% for 5,000 m. Finally, the effects of a 5% change in C_r amount to ~3.8% throughout. Thus, Table 4 shows that the most important variable for estimating best performances is C_r, followed by MAP, and finally by AnS.

All three sets of predicted records in this study [present data, data calculated from Lacour et al. (15), and world records] were obtained assuming "reasonable" AnS values, as from current literature. This is the weakest point of this approach, since AnS is a difficult quantity to assess precisely. As shown in Table 4, however, the effects of the errors in the assessment of AnS become vanishingly small for distances on the order of ≥3,000 m.

Table 2 shows that the agreement between calculated and actual performance times is rather good. Indeed, for distances between 1,500 and 5,000 m, the ratio of t_{act} to t_{calc} ranges from 1.015 to 1.038. For the shorter distances (800 and 1,000 m), the model overestimates performances. The reasons for this may be twofold. First, the time over these distances may be too short for full exploitation of the anaerobic capacity (see below). Second, over the shorter distances and higher speeds, $C_{r,tot}$ was not measured but was extrapolated from lower speeds. Therefore, the possibility cannot be ruled out that $C_{r,tot}$ at higher speeds increases more than predicted from *Eq. 8*, thus necessarily leading to an overestimation of speed.

The goodness of fit of the model can also be appreciated by the extremely high determination coefficient (r^2) of the regressions between t_{calc} and t_{act} (see Figs. 3 and 4). It is only fair to point out that these very high values of r^2 depend on the large range of t values. Thus the regressions between actual and calculated speeds were also determined. The corresponding r^2 of the pooled data amounted to 0.749 (n = 109; speed range: 4.60–7.692 m/s). When the performances over 800 and 1,000 m were neglected, r^2 increased to 0.852 (n = 76; speed range: 4.60–6.98 m/s).

The approach presented here was originally proposed by di Prampero (8–11) and further developed by Péronnet and Thibault (16). These authors' model yields very good predictions of actual records from 60 m to the marathon. Its main differences in comparison with the present model are as follows: *1*) the assumption, by Péronnet and Thibault, of larger values of both MAP and AnS for elite athletes (79.7 ml·kg^{-1}·min^{-1} for $\dot{V}O_{2\,max}$ above resting and 79.0 ml O_2/kg compared with 74 ml·kg^{-1}·min^{-1} and 68 ml O_2/kg for this study), *2*) the assumption that $\dot{V}O_{2\,max}$ cannot be maintained at the 100% level beyond the 7th min of exercise (14th min in this study), *3*) the assumption that at the onset of exercise the rate of the aerobic metabolism at the muscle level increases with a time constant of 30 s (10 s in this study), and the assumptions that the amount of energy available from the anaerobic stores *4*) increases with a time constant of 20 s up to the 7th min of effort and *5*) decreases for longer distances, being reduced to ~66% of the total

TABLE 4. *Predicted percent decrease in record times in indicated events with changes in MAP, AnS, Cr*

MAP (%):	100	100	100	105	105
AnS (%):	100	100	105	100	105
C_r (%):	100	95	100	100	95
Distance, km					
0.8	100.0 (98.7)	96.3 (95.0)	98.2 (97.0)	97.3 (96.0)	96.1 (94.9)
1.0	100.0 (130.2)	96.4 (125.2)	98.5 (128.3)	97.0 (126.2)	92.0 (119.8)
1.5	100.0 (210.1)	96.1 (202.0)	99.0 (208.1)	96.6 (203.0)	92.1 (193.5)
3.0	100.0 (451.9)	96.3 (435.1)	99.8 (450.1)	96.3 (435.5)	95.8 (416.9)
5.0	100.0 (776.4)	96.2 (747.4)	99.7 (774.1)	96.1 (746.7)	92.3 (716.9)

Values are percent decrease predicted with 5% change in maximal aerobic power (MAP), maximal anaerobic capacity (AnS), or C_r or when all three are changed by 5% simultaneously (last column). 100%: MAP = 1.8 kW, corresponding to $\dot{V}O_{2\,max}$ of 74 ml·kg^{-1}·min^{-1} above resting), AnS = 100 kJ (68 ml O_2/kg), C_r = 0.181 ml O_2·kg^{-1}·m^{-1} (3.79 J·kg^{-1}·m^{-1}) in a 70-kg, 175-cm elite athlete. Values in parentheses are record times (in s). For calculations see text.

for a 30-min effort. These last two assumptions together imply that MAP is entirely available only for exercises lasting between ~120 and 420 s. On the contrary, in the present study it was assumed that the anaerobic energy stores could be completely utilized for all t ranging from ~100 to 900 s.

Assumption 4 is crucial for predicting sprint running performances. It may indeed be the reason why in the present study the performances predicted for the 800 m are overestimated substantially compared with the actual ones (see Table 2). *Assumption 5* does not introduce great differences between the two models, since the contribution of the anaerobic energy stores becomes a progressively smaller fraction of the overall energy expenditure with increasing duration of effort (~5% of the total for t of 15 min; see *Eq. 5*). The other differences between the two models (*assumptions 1–3*) must obviously cancel out because they both fit the curve for the world records very well, at least between 800 and 5,000 m.

It must be pointed out, however, that when it comes to the evaluation of world records, both models suffer from the identical drawback of utilizing the same values of MAP and AnS for sprinters and middle- and long-distance runners.

Conclusions. The agreement between theoretical and actual performances emerging from the above discussion and calculations is fairly good, thus providing us with a clearer understanding of the energetics of running.

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