Differential modeling of anaerobic and aerobic metabolism in the 800-m and 1,500-m run

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Billat V, Hamard L, Koralsztein JP, Morton RH. Differential modeling of anaerobic and aerobic metabolism in the 800-m and 1,500-m run. J Appl Physiol 107: 478–487, 2009. First published May 28, 2009; doi:10.1152/japplphysiol.91296.2008.—This study examined the hypothesis that running speed over 800- and 1,500-m races is regulated by the prevailing anaerobic (oxygen independent) store (ANS) at each instant of the race up until the all-out phase of the race over the last several meters. Therefore, we hypothesized that the anaerobic power that allows running above the speed at maximal oxygen uptake (Vo2max) is regulated by ANS, and as a consequence the time limit at the anaerobic power (lim PAN = ANS/PAN) is constant until the final sprint. Eight 800-m and seven 1,500-m male runners performed an incremental test to measure Vo2max and the minimal velocity associated with the attainment of Vo2max (vVo2max), referred to as maximal aerobic power, and ran the 800-m or 1,500-m race with the intent of achieving the lowest time possible. Anaerobic power (PAN) was measured as the difference between total power and aerobic power, and instantaneous ANS as the difference between end-race and instantaneous accumulated oxygen deficits. In 800 m and 1,500 m, lim PAN was constant during the first 70% of race time in both races. Furthermore, the 1,500-m performance was significantly correlated with lim PAN during this period (r = –0.92, P < 0.01), but the 800-m performance was not (r = –0.05, P = 0.89), although it was correlated with the end-race oxygen deficit (r = –0.70, P = 0.05). In conclusion, this study shows that in middle-distance races over both 800 m and 1,500 m, the speed variations during the first 70% of the race time serve to maintain constant the time to exhaustion at the instantaneous anaerobic power. This observation is consistent with the hypothesis that at any instant running speed is controlled by the ANS remaining.

Exercise; oxygen; pace; performance

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THIS STUDY attempts to elucidate alterations in energetics during actual middle-distance track competition by examining how these fluctuations may be related to changes in running speed. For that purpose, since the best human performances in middle-distance running (800–10,000 m) are characterized by a speed variability of 5–10% (5, 15, 52, 57), the data were collected under actual race conditions. This is novel and extremely important as in many cases data collection using collected under actual race conditions. This is novel and extremely important as in many cases data collection using standard laboratory conditions may not truly reflect real-world performances. It is still not known how athletes regulate their speed to optimize performance in supramaximal races such as middle-distance events (26, 27). It is now possible to monitor athletes during real competitions on the track with a portable gas analyzer system coupled with a global positioning system (GPS) (5, 6, 55), and therefore we can simultaneously obtain both speed variations and energetics in the context of performance achievement. Even if control of speed and thus of power output is voluntary (5), the physiological signals that athletes receive for estimating their ability to sustain any instantaneously chosen speed have yet to be elucidated.

For exhaustive constant-speed runs performed between 90 and 120% of the velocity associated with the attainment of maximal oxygen uptake (vVo2max) and eliciting maximal oxygen uptake (Vo2max), i.e., above the critical speed (CS) that is the asymptote of the speed/time limit relationship (25), the estimation of the time limit to the end of the race has been shown to be accurate especially in well-trained subjects (26). Indeed, the Borg (9) rating of perceived exertion (RPE) vs. time limit scale was recently validated (27). When anaerobic power is elicited, both accumulated oxygen deficit (AOD) and lactate concentration increase as the exercise progresses, corresponding to the so-called “anaerobic capacity” i.e., a quantity of energy allowing some distance [the anaerobic distance capacity (ADC)] to be run without the resynthesis of ATP by oxidative phosphorylation (20, 29, 44). This anaerobic reserve called “anaerobic work capacity” is expressed in joules or in oxygen deficit or distance equivalent for a given energy cost of running in joules per kilogram per meter (19), and it has been demonstrated that the time to exhaustion performed at constant speeds between 90 and 140% of vVo2max could be well predicted by this reserve (8). To be in accord with the common literature we regard anaerobic energy and oxygen-independent energy as synonymous terms. For exhaustive variable-speed runs, it has been demonstrated that the number of repetitions of intermittent exercise cycles could be calculated with a decrease of the anaerobic reserve during the hard running phases and an increase during the recovery phases (47). Furthermore, the range of speed variation has been reported to depend on the ratio CS/ADC. This ratio, called the “endurance parameter ratio,” is considered to be an important determinant of the race-pace strategy, suggesting that the ability to vary running speed above the fatigue threshold speed depends on the ratio between the anaerobic reserve (ADC) and the fatigue threshold speed (CS) (25). In the same way, Ward-Smith (60) named the ratio between the anaerobic capacity and the maximal aerobic power as λ. Ward-Smith reported a λ value of 55 s, which is close to the duration of 400-m events. However, no studies have as yet examined the time course of this ratio during supramaximal exercise.

Middle-distance running of duration 2–4 min (800–1,500 m) elicits aerobic metabolism to its maximum power and anaerobic metabolism to its maximum capacity (6, 25, 55, 59). It has been demonstrated that Vo2max and maximal oxygen deficit are well correlated with performance in middle-distance races (800–1,500 m) (19). The power output above Vo2max

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elicited in 800- and 1,500-m races depends on the remaining anaerobic store as reflected by the accumulated oxygen deficit at each instant of the race. Therefore, sequential anaerobic power (PAN) that is momentarily elicited should depend on the remaining anaerobic stores (ANS) at that moment of the race and on the run duration at that sequential anaerobic power (tlim PAN) according to the following equation:

\[
PAN = \frac{ANS}{t\text{lim}\ PAN} \quad (1)
\]

or, from a more physiological viewpoint, the time that an athlete can sustain an anaerobic power is given by the ratio between the anaerobic store at that moment of the race and the anaerobic power at the same moment. That is:

\[
t\text{lim}\ PAN = \frac{ANS}{PAN} \quad (2)
\]

where PAN is in watts, ANS in joules and is estimated by the oxygen deficit during the race (6), and tlim PAN is in seconds. Given that the anaerobic stores are a finite quantity of energy, the middle-distance runner must elicit \( V\dot{O}_2\)max to minimize the ANS depletion before the final sprint. For that, the first part of the race must not be run too fast yet also be sufficient to achieve a good performance. Furthermore, it has recently been reported that 800-m runners demonstrated an oxygen uptake (\( V\dot{O}_2\)) drop below \( V\dot{O}_2\)max, which additionally taxes the anaerobic stores (55). This \( V\dot{O}_2\) drop could be due to the metabolic acidosis, which impairs mitochondrial respiration (30). Therefore, middle-distance speed must be as high as possible above the maximal aerobic power (i.e., the product of \( V\dot{O}_2\)max by the oxygen cost of running) to achieve a good final performance. For that, the first part of the race must not be run too fast yet also be sufficient to achieve a good performance. Furthermore, it has recently been reported that 800-m runners demonstrated an oxygen uptake (\( V\dot{O}_2\)) drop below \( V\dot{O}_2\)max, which additionally taxes the anaerobic stores (55). This \( V\dot{O}_2\) drop could be due to the metabolic acidosis, which impairs mitochondrial respiration (30). Therefore, middle-distance speed must be as high as possible above the maximal aerobic power (i.e., the product of \( V\dot{O}_2\)max by the oxygen cost of running) to achieve a good final performance but without depleting anaerobic stores too early and without decreasing \( V\dot{O}_2\) below \( V\dot{O}_2\)max by an inhibition of oxidative phosphorylation with early acidosis (11, 37, 53). Furthermore, the recent work of Jones et al. (32) on pacing strategy showed that a fast start would contribute to improved exercise tolerance because of a more rapid increase in oxygen uptake.

Noakes, St. Clair Gibson, and Lambert discuss the model of a central neural governor preventing the risk of anaerobiosis on oxygen-sensitive organs during maximal exercise (48, 49). Fatigue is hypothesized as being the result of the complex interaction of multiple peripheral physiological systems and the brain. In this model, all changes in peripheral physiological systems such as substrate depletion or metabolite accumulation act as afferent signalers that modulate control processes in the brain in a dynamic, nonlinear, integrative manner. A lot of the central governor theory is based on the work of Ulmer (57), who considered that afferent motor signals to skeletal muscles concerned not only the space/time pattern of motion but also the setting of muscular performance and through this the control of the current metabolic rate. He proposed that for an optimal adjustment of metabolic rate during heavy exercise, e.g., in athletic competitions, a feedback control system must exist, including a programmer that takes into consideration a finishing point (teleoanticipation). He showed different time delays between the perception of level of exertion (RPE scale) and those of the heart rate (HR), which support his hypothesis that perceived exertion is part of the feedback system for optimal adjustment of exertion. He concluded that when exercise is long enough there is enough time, such as when a plateau of HR for instance is reached, to include energy reserves for a final spurt. This “central governor” model proposes that the subconscious brain regulates power output (pacing strategy) by modulating motor unit recruitment to preserve body homeostasis and prevent catastrophic physiological failure such as rigor (48).

The present study examines the hypothesis that running speed is regulated by the prevailing anaerobic store at each instant of the race. If this hypothesis can be supported, despite the progressive depletion of the anaerobic stores, then PAN at each instant of the race would allow a time to exhaustion at PAN (tlim PAN) to be maintained constant until the last several meters of the race, whereupon it becomes an all-out rather than a controlled exercise.

MODELING RATIONALE

Equations 1 and 2 are interpreted in the context of a general two-component (aerobic and anaerobic) bioenergetic system. The simplest such system is the two-parameter critical power model (46). This simple model, however, does not incorporate any control over power output. The hypothesis that achievable power output or running speed may be controlled in some way by the remaining ANS has been suggested and modeled previously (43). Such modeling has been demonstrated, supported, and illustrated with constant-power exercise on a cycle ergometer (44). This three-parameter critical power model has been the subject of a number of subsequent studies (10, 13, 17, 46). This hypothesis has not to our knowledge been adequately examined with respect to actual track running, and it remains to be demonstrated whether a constant tlim PAN is indeed mathematically consistent with this model. Below we verify this consistency, in order that data collected in these circumstances and evidencing this constancy does indeed support the hypothesis.

Suppose, as suggested above, we hypothesize that

\[
t\text{lim}\ PAN = \frac{ANS}{PAN} = k_1 (\text{a constant}) \quad (3)
\]

where instantaneous ANS is given by the difference between end-race and instantaneous oxygen deficits. Now the end-race oxygen deficit is some fixed value (say \( k_2 \)), and instantaneous oxygen deficit is the integral of PAN (denoted by the variable \( x \)) up to that instant. Consequently this simple equation takes the form:

\[
(k_2 - x)/x' = k_1 \quad (4)
\]

where \( x' = \text{PAN} \) is the derivative of \( x \). That is:

\[
x' = k_2/k_1 - x/k_1 \quad (5)
\]

This is a simple first-order linear differential equation whose solution is \( x = k_2(1 - e^{-kt}) \), which is exactly the same form as that which has previously been shown to represent the optimal strategy for running a given distance in minimal time under the control system assumption hypothesized above (45). It follows therefore that if data on ANS and PAN are collected serially during a race and (if they change at the same rate) demonstrate a constant ratio over at least a significant part of that race (excluding maybe the final sprint), then our hypothesis would be supported.

POWER SYSTEMS ESTIMATION BY GAS EXCHANGE

We estimated the anaerobic power and anaerobic work capacities with gas exchange according to previous validation.
METHODS

Subjects

The subjects included 15 male middle-distance runners; 8 were specialists over 800-m and 7 over 1,500-m races. The two groups had previously attained similar levels of achievements (in number of points on the IAAF scoring tables) and presented no significant differences in aerobic characteristics (included with race results in Table 1 for comparison of maximal VO$_2$ reached during the races).

Table 1. Maximal values of V O$_2$ and HR of the race compared with the maximal values measured in the incremental test and anaerobic capacity during the races (estimated by the accumulated oxygen deficit at the end of the race) for the 800-m race and the 1,500-m race

<table>
<thead>
<tr>
<th>Subjects</th>
<th>VO$_{2max}$</th>
<th>max VO$_{2race}$</th>
<th>vVO$_{2max}$</th>
<th>vVO$_{2race}$</th>
<th>HR$_{max}$</th>
<th>max HR$_{race}$</th>
<th>Lactate max$_{race}$</th>
<th>V$_{race}$</th>
<th>Cr</th>
<th>ml·kg$^{-1}$·m$^{-1}$</th>
<th>Racing Time t$<em>{800}$ or t$</em>{1500}$</th>
<th>s; Rank in Race</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>70.0; 71.0</td>
<td>20.0; 21.2</td>
<td>190; 190</td>
<td>12.7; 14.4</td>
<td>105.9</td>
<td>0.210</td>
<td>136; 7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>60.0; 57.4</td>
<td>19.0; 22.8</td>
<td>185; 183</td>
<td>14.2; 16.1</td>
<td>120.0</td>
<td>0.189</td>
<td>126; 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>64.8; 62.4</td>
<td>18.0; 20.6</td>
<td>196; 196</td>
<td>12.1; 15.8</td>
<td>114.3</td>
<td>0.216</td>
<td>147; 8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>62.7; 60.6</td>
<td>19.0; 24.0</td>
<td>195; 194</td>
<td>11.4; 18.0</td>
<td>126.3</td>
<td>0.198</td>
<td>120; 1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>5</td>
<td>66.0; 65.2</td>
<td>20.0; 22.6</td>
<td>195; 194</td>
<td>13.7; 20.8</td>
<td>113.0</td>
<td>0.198</td>
<td>127; 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>62.7; 60.8</td>
<td>19.0; 22.1</td>
<td>195; 193</td>
<td>12.0; 17.3</td>
<td>116.1</td>
<td>0.198</td>
<td>131; 6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>66.0; 65.2</td>
<td>20.0; 23.0</td>
<td>199; 200</td>
<td>15.0; 16.3</td>
<td>115.0</td>
<td>0.198</td>
<td>125; 2</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>8</td>
<td>66.5; 68.0</td>
<td>19.0; 22.3</td>
<td>195; 194</td>
<td>16.0; 16.8</td>
<td>117.4</td>
<td>0.210</td>
<td>129; 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>64.8; 63.8</td>
<td>19.3; 22.3</td>
<td>194; 193</td>
<td>13.4; 16.9</td>
<td>116.0</td>
<td>0.202</td>
<td>129</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P = 0.1</td>
<td>3.0; 4.4</td>
<td>0.7; 1.1</td>
<td>4; 5</td>
<td>1.6; 1.9</td>
<td>5.9</td>
<td>0.009</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

For the 800-m or 1,500-m race, VO$_{2max}$ is the maximal oxygen uptake achieved in the incremental test; max VO$_{2race}$ is the maximal value of oxygen uptake achieved during the race; vVO$_{2max}$ is the velocity associated with VO$_{2max}$ in the incremental test; Lactate max$_{race}$ is the maximal blood lactate accumulation measured at the end of the incremental test; Lactate$_{race}$ is the lactate at the end of the race; V$_{race}$ is the average velocity over the 800-m or 1,500-m run expressed in km/h and in percentage of vVO$_{2max}$; HR$_{max}$ is the maximal heart rate reached during the incremental test; max HR$_{race}$ is the maximal heart rate reached during the 800-m or 1,500-m race; and Cr is the energy cost of running. Subjects are different subjects over 800-m and 1,500-m run races.
Table 2. Individual physical characteristics and performance of the metabolic power of athletes required to run the 800 m and 1,500 m at their personal best

<table>
<thead>
<tr>
<th>Subjects</th>
<th>Weight, kg</th>
<th>Height, cm</th>
<th>Age, yr</th>
<th>Fat mass, %</th>
<th>Racing Time, ( t_{800} ) or ( t_{1500} ), s</th>
<th>Personal Best, s</th>
<th>% of Personal Best</th>
</tr>
</thead>
<tbody>
<tr>
<td>800-m race</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>66</td>
<td>183</td>
<td>17</td>
<td>10.6</td>
<td>136.0</td>
<td>134.0</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>74</td>
<td>179</td>
<td>19</td>
<td>13.6</td>
<td>126.0</td>
<td>112.8</td>
<td>89</td>
</tr>
<tr>
<td>3</td>
<td>61</td>
<td>180</td>
<td>17</td>
<td>7.0</td>
<td>120.0</td>
<td>108.0</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>69</td>
<td>185</td>
<td>19</td>
<td>7.0</td>
<td>127.1</td>
<td>127.1</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>66</td>
<td>180</td>
<td>19</td>
<td>12.1</td>
<td>131.0</td>
<td>129.0</td>
<td>99</td>
</tr>
<tr>
<td>6</td>
<td>74</td>
<td>178</td>
<td>17</td>
<td>11.8</td>
<td>125.0</td>
<td>116.0</td>
<td>93</td>
</tr>
<tr>
<td>7</td>
<td>72</td>
<td>184</td>
<td>19</td>
<td>12.3</td>
<td>129.0</td>
<td>126.0</td>
<td>98</td>
</tr>
<tr>
<td>Mean</td>
<td>68</td>
<td>181</td>
<td>18</td>
<td>10.4</td>
<td>129.6</td>
<td>124.1</td>
<td>96</td>
</tr>
<tr>
<td>SD</td>
<td>5</td>
<td>3</td>
<td>1</td>
<td>2.5</td>
<td>6.0</td>
<td>11.0</td>
<td>4</td>
</tr>
</tbody>
</table>

| 1,500-m race | | | | | | | |
| 1 | 53 | 168 | 17 | 11.0 | 263 | 249 | 95 |
| 2 | 76 | 190 | 18 | 13.0 | 270 | 247 | 91 |
| 3 | 50 | 170 | 18 | 12.0 | 268 | 250 | 93 |
| 4 | 65 | 180 | 18 | 11.0 | 250 | 244 | 98 |
| 5 | 60 | 169 | 17 | 10.0 | 314 | 275 | 88 |
| 6 | 59 | 175 | 18 | 12.0 | 268 | 253 | 94 |
| 7 | 52 | 162 | 18 | 13.0 | 256 | 237 | 93 |
| Mean | 59 | 173 | 18 | 11.7 | 270 | 251 | 93 |
| SD | 9 | 9 | 1 | 1.1 | 21 | 12 | 3 |

Subjects are different subjects over 800-m and 1,500-m run races.

1710, Arkray, Kyoto, Japan. This lactate analyzer was calibrated before all tests (42).

Exercise Tests

Incremental test. To measure the energy cost of running at different speeds, the subjects first performed a paced incremental test with 3-min stages on a track (6). During the last 6 min of a 10-min warmup at a speed of 12 km/h, when anaerobic metabolism is negligible and when there is no slow component of oxygen uptake kinetics, the oxygen cost (Cr) at this submaximal speed was measured. Thereafter the subjects ran at 14 km/h and speed was progressively increased by 1 km/h at each stage. A fingertip capillary blood sample was collected immediately before and 3 min after the test. \( V_{O2max} \) was defined as the plateau attained by oxygen uptake during this incremental test or if no decrease in \( V_{O2} \) was attained during the last two stages (6).

The last stage, it was then considered as the averaged velocity main-

Middle-distance (800 m and 1,500 m) races. One week later, the subjects competed in an 800-m or 1,500-m race in a competition organized by the French Athletic Federation. Before the competition period, the subjects were no longer available to perform tests to measure their maximal accumulated oxygen deficit [an all-out run of 2 min according to the protocol of Medbo et al. (41)]. Time limit at \( V_{O2max} \) was computed as the total racing time minus the time delay for reaching \( V_{O2max} \) and the \( V_{O2} \) drop duration.

Description and Calculation of Physiological Data

Net oxygen cost of running. The net oxygen cost of running, \( Cr \), is defined as the per kilogram body weight oxygen equivalent of the energy required above resting (estimated by \( V_{O2} - V_{O2rest} \)) to transport the subject’s body over one unit of distance (19).

\[
Cr = (V_{O2} - V_{O2rest})/v
\]  

where \( V_{O2} \) is the oxygen uptake at the mean velocity \( v \) and is expressed in milliliters per kilogram per minute. Given that the runners were not really at rest before the race we assumed a \( V_{O2} \) at rest \( (V_{O2rest}) \) to be equal to \( 5 \) ml kg\(^{-1}\) min\(^{-1}\) according to the intercept of the \( V_{O2} \)-speed regression line obtained by Medbo and Tabata (39, 41). \( v \) is the velocity in meters per minute, and thus \( Cr \) is the oxygen cost of running in milliliters \( O2 \) per kilogram per meter. \( Cr \) is estimated by the oxygen uptake at submaximal speed, i.e., during the last 6 min of the 10-min warmup at 12 km/h in the incremental test. The oxygen cost required according to the speed during the 800-m or 1,500-m races \( (V_{O2demand}) \) was calculated according to Eq. 7 (19):

\[
V_{O2demand} = v_{race} \times Cr
\]

where \( v_{race} \) is the 800-m or 1,500-m racing speed. This formula assumes that the energy cost of running is independent of running velocity according to di Prampero (18) and other authors (31). This assumption is also a condition of the validity of the critical power (speed) model and its derivatives (46). At these speeds the aerobic-dynamic component of the energy cost of running is still of the same order of magnitude as that of the experimental error of measurement (5\%) (6).

Accumulated \( O2 \) deficit calculation during the 800-m and 1,500-m races. Every 5 s, the oxygen deficit (\( O2 \) deficit expressed in ml \( O2 \)/kg) was calculated as the difference between the oxygen demand \( (V_{O2demand}) \), ml kg\(^{-1}\) min\(^{-1}\) according to the speed (m/min) multiplied by the energy cost of running (ml \( O2 \)/kg\(^{-1}\) min\(^{-1}\)), and the effective oxygen uptake \( (V_{O2}) \) ml kg\(^{-1}\) min\(^{-1}\). The accumulated \( O2 \) deficit was the whole race oxygen deficit and was the sum of all 5-s oxygen deficits during the race.
**Instantaneous time limit at the anaerobic power (tlim PAN)**. The time limit at the anaerobic power (tlim PAN) was calculated according to Eq. 2, which represents the maximal duration that the runner could sustain at this anaerobic power at this instant of the race given the anaerobic stores at the time. Speed variability was defined using the coefficient of the variation (i.e., the ratio between the speed SD and the mean speed, multiplied by 100).

**Statistics**

Because of the small sample sizes in this study (n = 7 and n = 8), the normality of the distribution and the equality of the variance were checked by SigmaStat (Jandel Scientific, Chicago, IL). When the normality of the distribution and the equality of the variance were verified, an ANOVA test on one factor (racing distance effect, 800 vs. 1,500 m) or two factors (distance and the first vs. second part of the race) was applied to measure the racing distance and fatigue effect during each race on tlim PAN (Staview 5.5, Statsoft, Berkeley, CA); if not, a Mann-Whitney U-test was applied. The two parts of the race were split according to racing time and not running distance since we focused on tlim PAN and not on the distance limit at PAN. Correlations between VO2max, total accumulated oxygen deficit (TAOD), %AN, speed variability, and performance were determined using Pearson’s product-moment correlation coefficient. A chi-squared test was performed to test the association between racing distance and the occurrence of the VO2 drop. We do not necessarily adopt the common but arbitrary 5% level for statistical significance. Exact P values are quoted for all tests, and statistical and practical significances are discussed on a case-by-case basis. This will also permit readers to form their own assessments as to the importance of our results. All results are presented as means ± SD.

**RESULTS**

**Performance Times (t800 and t1500)**

All the runners ran at a speed equal to or superior to 90 and 95% of their absolute personal best or equal to or superior to the performance accomplished at the same period of the year (in the early phase of the competition period) (96 ± 4 vs. 93 ± 3% for the 800-m and 1,500-m runners, P = 0.19) (Table 2). The runners elicited their maximal VO2 and HR, average racing speed (v800 and v1500) was above that of the speed associated with VO2max (vVO2max) (116.0 ± 5.9 and 105.1 ± 5.6% of vVO2max, P = 0.002), and the postrace maximal blood lactate concentrations were equal to 16.9 ± 1.9 and 15.3 ± 2.6 mM after the 800-m and 1,500-m races, respectively (P = 0.18) (Table 1).

**Racing Speed Variations and Correlation with Performance**

Running speed ranges were 5.8 ± 1.3 vs. 7.5 ± 2.3 m/s over 800 m and 1,500 m. However, when this coefficient of speed variation was expressed relative to the average speed (27.0 ± 7.1% and 52.8 ± 13.6%), the speed range was significantly higher during the 800-m race compared with the 1,500-m race (P < 0.001). Typical speed patterns of one 800-m runner (Fig. 1A) and one 1,500-m runner (Fig. 1B) showed that over 800 m, the speed continuously decreased as if in an all-out exercise (Fig. 1A), while over 1,500 m the speed reached a plateau with fluctuations above vVO2max (Fig. 1B). This higher speed amplitude over 800 vs. 1,500 m was confirmed by the higher coefficient of the 800-m speed variation (11.5 ± 4.1% vs. 8.3 ± 3.3% over 800 and 1,500 m, respectively, P = 0.003). In both races, the coefficients of variation of the speed during the second half of the races were significantly lower than those observed during the first half of the races (CVs = 3.2 ± 1.4% and 8.0 ± 3.3% for the last part of the 800 and 1,500 m, P = 0.006). Performance was related to the variability of running speed for the 800-m race (r = −0.712, P = 0.047) but not for the 1,500 m (r = 0.24, P = 0.606). Thus the higher the variability over 800 m, the better was the performance (i.e., lower t800).

**Time Limit at the Momentary Anaerobic Powers (tlim PAN) and at VO2max and Correlation with 800- and 1,500-m Performances**

Sequential speeds elicited a PAN that the athlete was able to sustain for 32% of the final racing time (tlim PAN = 34.0 ± 8.0 and 31.9 ± 12.2% of t800 and t1500, P = 0.68) (Table 3). However, after two-thirds of the racing time, tlim PAN had dropped (62 ± 13 and 63 ± 14% of t800 and t1500, respectively, P = 0.91). The average value of tlim PAN was significantly longer in the first compared with the second half of the 800-m (57 ± 14 vs. 32 ± 6 s, P = 0.01) and 1,500-m (107 ± 36 vs. 74 ± 41 s, P = 0.01) races (Table 3). Over 1,500 m, tlim PAN was not influenced by the delay of attainment of VO2max since it was not significantly different before and after the attainment of VO2max (96 ± 32 vs. 78 ± 32 s, P = 0.32). In contrast, over 800 m tlim PAN appeared (considering the risk of type I error and the interindividual variation) to be related to the attainment of VO2max (57 ± 16 vs. 43 ± 11 s, P = 0.06). In addition, tlim...
PAN was not influenced by the $V\dot{O}_2$ drop ($r = 0.455, P = 0.49$). These final two results are crucial and show that the ability to maintain $V\dot{O}_2_{max}$ at the end of the race did not influence the time to exhaustion at the momentary anaerobic power.

The time limit at $V\dot{O}_2_{max}$ (tlim $V\dot{O}_2_{max}$) expressed as a percentage of the racing duration was also not significantly different between 800 m and 1,500 m (61 ± 10 vs. 71 ± 13% of the racing time over 800 m and 1,500 m, $P = 0.13$) (Table 4). In the final part of the race, half of the group (8/15) demonstrated a $V\dot{O}_2$ drop below $V\dot{O}_2_{max}$ that appeared over the final 10% of the race, and three of them increased their speed and two maintained it by increasing their speed and then eliciting their anaerobic power in the final sprint using the remaining aerobic stores. Their performances were not correlated with the time limit at $V\dot{O}_2_{max}$ expressed either in seconds or in percent of the racing time ($P = 0.64$ and 0.80 for $t_{800}$ and $P = 0.71$ and 0.22 for $t_{1500}$).

The AOD, which depends on the speed run above $V\dot{O}_2_{max}$ and time sustained at $V\dot{O}_2_{max}$ considered beforehand, represents the progressive depletion of the anaerobic stores. AOD increased linearly throughout the race until the finish as shown in Fig. 2, A and B. The TAOD was negatively correlated with performance over 800 m ($t_{800}$) ($r = -0.70, P = 0.05$), meaning that for the 800 m, the higher the oxygen deficit, the better the performance (lower $t_{800}$), but not significantly correlated over 1,500 m ($t_{1500}$) ($r = -0.51, P = 0.26$).

**DISCUSSION**

This study has, for the first time, taken a bioenergetic approach to running speed variation and performance as measured during actual race conditions, despite the inherent practical difficulties in obtaining such measurements. We have taken this approach in an attempt to understand how a runner selects running speed so as to optimize real-world performance using energetic resources.

The originality of this study was to adapt the calculation to the data measured during an actual race providing continuous estimation of aerobic power from oxygen uptake and anaerobic power from the deficit in oxygen. It overcomes two major limits of the original approach based on the use of constant-power tests and assuming an infinitely fast increase in aerobic limits of the original approach based on the use of constant-power tests and assuming an infinitely fast increase in aerobic power. This is because the constant-power model does not incorporate any $V\dot{O}_2$ kinetics but it has been demonstrated that a fast-start pacing strategy allows achievement of optimal performance under the assumptions of the three-parameter model (45).

This study shows that speed control in middle-distance races is such as to maintain the time to exhaustion at the instantaneous anaerobic power (tlim PAN = ANS/PAN) constant.
Table 4. Time to exhaustion at the anaerobic power in the whole race and in the first and second half part of the race

<table>
<thead>
<tr>
<th>Subjects</th>
<th>800-m race</th>
<th>1,500-m race</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tim PAN on Whole Race, s (% of ( t_{800} ) or ( t_{1500} ))</td>
<td>tim PAN on First Half, s (% of ( t_{800} ) or ( t_{1500} ))</td>
</tr>
<tr>
<td>1</td>
<td>39.8 (29.3%)</td>
<td>49.4 (36.3%)</td>
</tr>
<tr>
<td>2</td>
<td>47.0 (37.2%)</td>
<td>60.5 (48.0%)</td>
</tr>
<tr>
<td>3</td>
<td>34.3 (24.5%)</td>
<td>39.6 (28.3%)</td>
</tr>
<tr>
<td>4</td>
<td>37.8 (31.5%)</td>
<td>51.8 (43.2%)</td>
</tr>
<tr>
<td>5</td>
<td>47.8 (37.5%)</td>
<td>59.9 (47.2%)</td>
</tr>
<tr>
<td>6</td>
<td>54.5 (41.7%)</td>
<td>74.1 (56.6%)</td>
</tr>
<tr>
<td>7</td>
<td>30.7 (24.6%)</td>
<td>39.6 (31.6%)</td>
</tr>
<tr>
<td>8</td>
<td>59.5 (46.1%)</td>
<td>79.4 (61.6%)</td>
</tr>
<tr>
<td>Mean</td>
<td>43.9 (34.0%)</td>
<td>56.7 (44.0%)</td>
</tr>
<tr>
<td>SD</td>
<td>10.1 (8.0%)</td>
<td>14.7 (11.6%)</td>
</tr>
<tr>
<td>1</td>
<td>98.4 (37.4%)</td>
<td>131.3 (49.9%)</td>
</tr>
<tr>
<td>2</td>
<td>99.5 (36.9%)</td>
<td>138.5 (51.3%)</td>
</tr>
<tr>
<td>3</td>
<td>62.9 (23.5%)</td>
<td>81.2 (30.3%)</td>
</tr>
<tr>
<td>4</td>
<td>108.2 (43.3%)</td>
<td>129.9 (52.0%)</td>
</tr>
<tr>
<td>5</td>
<td>27.2 (8.7%)</td>
<td>38.6 (12.3%)</td>
</tr>
<tr>
<td>6</td>
<td>85.3 (31.8%)</td>
<td>107.4 (40.1%)</td>
</tr>
<tr>
<td>Mean</td>
<td>83.9 (31.9%)</td>
<td>106.6 (40.3%)</td>
</tr>
<tr>
<td>SD</td>
<td>29.5 (12.2%)</td>
<td>35.6 (14.6%)</td>
</tr>
</tbody>
</table>

Whichever the race distance \( (P = 0.69) \), time to exhaustion at the anaerobic power \( (t_{lim \, PAN}) \) is significantly lower in the second vs. the first half time of the race \( (P = 0.013) \). Considering the whole race, \( t_{lim \, PAN} \) is lower over 800 m vs. 1,500 m \( (P < 0.001) \) in absolute but not in relative time to \( t_{800} \) and \( t_{1500} \) \( (P = 0.81) \). Subjects are different subjects over 800-m and 1,500-m run races.

During ~70% of the racing time. This result suggests that the time spent running at the chosen instantaneous anaerobic power during this portion of middle-distance races may be a consequence of an anaerobic energetic controller of speed. This may well be related to the perception of exhaustion as previously reported for blood lactate accumulation (9). Furthermore, 1,500-m performance is related to \( t_{lim \, PAN} \), which depends on a careful first half racing speed selection, while performance over 800 m is related to the total anaerobic stores. Furthermore, \( t_{lim \, PAN} \) decreased almost significantly \( (P = 0.06) \) after the initial phase of \( \dot{V}_{O2\,\,\text{max}} \) steady-state achievement in the 800-m but not the 1,500-m race.

**Time Limit at the Instant Racing Anaerobic Power (t_{lim \, PAN}) is Maintained Constant During the First 70% of the Racing Duration**

Our results show that the sequential time limit at the anaerobic power \( \text{(t}_{lim \, PAN} \text{)} \) was constant during the first two-thirds of the racing time in both the 800 m and 1,500 m. This time limit is similar to the concept of the “endurance parameter ratio” proposed in a previous study by Fukuba and Whipp (25). This ratio has the dimension of duration (since it is a distance divided by speed) and has been interpreted to be a time limit before exhaustion (25). That is, speed variation has been reported to depend on the ratio of the anaerobic capacity (or the distance covered without the resynthesis of ATP by oxidative phosphorylation) to the critical speed. This index is considered to be an important determinant of the race-pace strategy (25), suggesting that the ability to vary running speed above the critical speed depends on the ratio between the anaerobic reserve, the anaerobic work capacity in joules (or distance equivalent for a given energy cost of running set in J·kg\(^{-1}·m\(^{-1}\)), and the fatigue threshold speed. The values of \( t_{lim \, PAN} \) reported in the present study for 1,500 m are close to the \( \lambda \) value Ward-Smith calculated (60) for long sprints (400 m). However that model was a constant-speed model, which is not necessarily optimal for achieving the best performance (i.e., the best average speed) (7, 24).

The present study showed that the time limit at the instantaneous anaerobic power remained constant until ~30% of the remaining racing time. These results indicate that this sequential time limit at the chosen anaerobic power may be a potential factor in regulating speed variations during supramaximal running races (800–1,500 m). Since the time limit at the instant anaerobic power is the ratio of the instant anaerobic stores and anaerobic power, we hypothesized that the reserves of anaerobic energy at each instant of the race could be one candidate for the feedback controllers of the power output, or more particularly of the anaerobic power. However, this does not exclude the possibility as reported for the marathon by Noakes (48), of the action of a central (brain) neural control that regulates performance “in anticipation” as recently suggested by the model of central neural control. Indeed, a large component of the complete central governor discusses and incorporates energetic feedback mechanisms, as described particularly in the manuscript of Noakes et al. (49). However, middle-distance events that are run in <5 min appear to have an energetic feedback mechanism that allows the last 30% of the racing time to be run without decreasing speed below the maximal aerobic speed. Our study may have been more complete if we had also examined the relationship between RPE, estimated time limit [ETL (24)], acidosis (pH), and the anaerobic deficit during race simulations on the treadmill, but the runners were not available for additional experiments as the competitive season had started. Garcin and Billat (26) previously demonstrated that an athlete was able to estimate his or
like an all-out race during which the first 200 m are run in start and speed decrease over 800 m. The 800-m race is more size and/or the high interindividual variation linked to the fast over 800 m may be due to a type 1 error due to small sample V˙O₂max over 800 m but not over 1,500 m. The

The method of estimating the oxygen deficit by gas exchange has been demonstrated to enable noninvasive quantification of the relative aerobic/anaerobic metabolism contributions (36) and has been extensively used in previous studies (16, 39, 61). The accumulated oxygen deficit at any one instant of the race is proportional to lactate accumulation and HR increase and may be associated with the time limit that an athlete is still able to sustain at that instant of the race (20). The estimation of the time limit during exhaustive exercise between 90 and 120% of V˙O₂max has been shown to be accurate especially in well-trained subjects. The estimation of a time limit scale has been validated for predicting the effective time limit at a given speed (27, 28). At any instant of the race, a runner is able to gauge the time limit at his or her running speed and in middle-distance running the time limit at the anaerobic power determines any speed fluctuation. Furthermore, it has been shown in an all-out 30- to 36-s exercise that there appeared to be a preprogrammed 30-s “end point” based on the anticipated exercise duration from previous experience, and that the changes in power output generated by the brain could be in response to peripheral metabolic changes in the active muscles (1). A minimal duration of 30 s may be required for efficacy of such controls. In the present study, the runner adopted a speed allowing him to elicit an anaerobic power that could be sustained for a time limit of 50 or 100 s, representing 30% of the remaining duration of the race, maintaining this until the last third part of the race. This capacity for estimating the time limit remaining has been reported to be fitness dependent since the runners who had the highest V˙O₂max were those who estimated ETL more accurately (28). However in the Garcin et al. studies (26, 28), running speed was imposed on the athlete and was maintained constant (at vV˙O₂max). Therefore, the perception of the time limit remaining at a sequential speed maintained for only a few seconds remains an unexplored domain that could be solved through an interdisciplinary approach between physiology and perceptual motor skills. The data obtained from the present study suggest that the athlete perceives the relative time for the total duration of the race (tlim PAN). It would be relevant to examine whether this scale is valid when the choice of speed is free as during a race. Even if the runners were asked to adopt a speed of their own choice and not according to the speed of their opponents, it is impossible to deny the likelihood that tactical aspects take into account the other runners, especially among those who had similar per-

Fig. 2. Typical time course of the oxygen volume (V˙O₂), and accumulated oxygen deficit (AOD) over 800 m (A) and 1,500 m (B) races for subject 4 of the 800-m group and subject 4 of the 1,500-m group, respectively.
sonal best times. However this race was performed in the early stage of the competition season and was considered by coaches as fine tuning between the regional championships. 

**Time Limit at the Anaerobic Power (tlim PAN) and Performance in Middle-Distance Races**

The question we asked was whether performance over middle-distance running was correlated with the momentary anaerobic power and its time to exhaustion and/or to the oxygen deficit. The best 1,500-m runners were those who recorded the higher time limits at the anaerobic power in the first two-thirds of the race thanks to a lower speed start. While this was the case for the 1,500-m runners, the best 800-m runners were those who demonstrated the highest anaerobic capacity (total oxygen deficit) at the end of the race. The 800-m performance has previously been reported to be related to the accumulated oxygen deficit in middle-distance runners (11, 53). The 800-m performance could rely on the capacity to buffer the \( \text{H}^+ \) inevitably produced during the race, which is rather more like an all-out race without any recovery and speed fluctuation around a plateau (55). Furthermore, high lactate exchange ability has been reported to be correlated with the 800-m but not with the 1,500-m performance in well-trained specialized subjects and could play a role in the athlete’s capacity to sustain exercise of close to 2-min duration and specifically to run 800 m (12). The 1,500-m performance was neither correlated with the maximal oxygen deficit nor with the anaerobic power but with their ratio (tlim PAN) averaged in the first two-thirds of the race. This means that over 1,500 m the runners who had the longest limits at their anaerobic power in the first part of the race were those who achieved the best final performance. The 1,500-m run could therefore require a closer control of speed while the 800-m race is more like a long sprint, at least for the first two-thirds of the race.

**Conclusion**

The present study supports the contention that in supramaximal middle-distance races (800 and 1,500 m) eliciting \( \dot{V}O_2_{\text{max}} \), running speed varies according to the anaerobic power in such a way as to maintain the time limit at the given sequential anaerobic power constant until the last third of the racing time. This finding is independent of the appearance of a \( \dot{V}O_2 \) drop at the end of the race observed in half of our runners and previously reported in a study over 800 m (55) and in laboratory conditions with a standard cart system (50). Only two runners were unable to manage their speed to maintain their time limit at PAN above 0 before the end of the race. The best 1,500-m runners were those who achieved the highest time limits at the anaerobic power in the first two-thirds of the race, and the best over 800 m were those who achieved the highest total accumulated oxygen deficit. These results suggest that the best 1,500-m performance depends on the runner’s ability not to start too fast involving a lower anaerobic power (keeping a longer time limit at the anaerobic power), while the 800-m run, which tends to be more like all-out exercise, may depend more on the total oxygen deficit that the athletes can bear before exhaustion. The anaerobic reserve may therefore determine the time to go at any instantaneous speed above \( \dot{V}O_2_{\text{max}} \) and could be part of an energetic controller set to be included in a model of central fatigue that is currently under debate (54). The present report has been a new approach to the energetics of middle-distance running, examining speed variation during real races. The present report can be viewed as a preliminary study before studies are carried out on the optimization of middle-distance performance in terms of speed management (5, 6, 7, 15).

We recognize that this was the only variable measured and uses indirect methods of measurement. Equally, a large number of other peripheral, cardiac, and/or neural factors could, and probably are, involved in creating variation in running speed during these events.

**ACKNOWLEDGMENTS**

We thank the runners for having agreed to wear the K4b² during a real competition, and the meeting organizers for admitting this “special” race into their meeting program.

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