The bioenergetics of optimal performances in middle-distance and long-distance track running

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Abstract

Aspects of anaerobic and aerobic energy conversion are investigated using a mathematical model of running in conjunction with world-record statistics. Analysis of the data shows that over distances from 1500 to 10,000 m the anaerobic energy utilised is constant and independent of running distance. This result is consistent with the view that the full potential of the anaerobic capacity is available for conversion during extended periods of running; the opinions of Gollnick and Hermansen (1973) and Peronnet and Thibault (1989) that the anaerobic energy contribution declines with race duration are not corroborated. The analysis supports the finding of Peronnet and Thibault (1989) that, for running times below about 420 s, the maximum sustainable aerobic power is constant, and that for larger it then declines progressively. The present analysis shows it falls by some 4.5% over 10,000 m, indicating that in establishing current world records at 5000 and 10,000 m athletes did not rely solely on glycogen as the source of aerobic metabolism; limited use was made of free fatty acids. For elite male runners, the anaerobic capacity and maximal aerobic power are evaluated as 1570 J/kg and 27.1 W/kg, respectively.

Keywords: Athletics; Running; Biomechanics; Bioenergetics; Aerobic; Anaerobic

1. Introduction

At the start of any vigorous exercise, such as competitive running, the initial source of muscular energy is anaerobic. The power available from this source quickly diminishes and, during periods of sustained running, aerobic metabolism is brought into play. For distances greater than about 800 m, aerobic metabolism is the principal source of energy, and the optimal utilisation of the aerobic pathway is brought about by minimising energy expenditure. This minimum corresponds to running at constant speed. There are two main fuel stores, namely glycogen and fats, available for oxidation. Whereas the body has a vast store of fat, the amount of glycogen is quite small. The musculature of a typical male athlete of 70 kg who has eaten a high carbohydrate diet in the build-up to competition will contain a maximum of about 500 g of glycogen. For a given volume of oxygen, the chemical conversion of body fat yields a smaller amount of energy than the aerobic conversion of glycogen. Hence an athlete can run faster when obtaining energy from the oxidation of glycogen rather than body fat. Aerobic power declines under conditions of sustained distance running and there are several factors which become important at various stages. They include (i) the replacement of muscle glycogen as a substrate by free fatty acids, and (ii) thermo-regulatory heart drift, i.e. the tendency of heart rate to increase with running time. Over extreme distances, muscle and liver glycogen depletion, together with a fall in the blood glucose level and a rise in blood tryptophan, are the major causes of fatigue (Newsholme et al., 1992).

The use of running records to derive bioenergetic and physiological data was first established as long ago as 1925 through the pioneering work of Hill (1925). A broad survey of the field was subsequently published by Jokl and Jokl (1968). In recent years the subject has been further developed by several successful mathematical analyses of running, covering distances from 100 m up to the marathon distance (Lloyd, 1967; Ward-Smith, 1985; Di Prampero et al., 1993; Peronnet and Thibault, 1989; Ward-Smith and Mobey, 1995). In direct methods of analysis, running performance is predicted by substituting physiological data into theoretical relationships; in
the inverse process physiological data are deduced from an analysis of running performance.

This paper utilises world record statistics to gain insights into two important aspects of anaerobic and aerobic energy conversion during middle- and long-distance running. Anaerobic capacity is defined as the maximum amount of energy that can be obtained through anaerobic metabolism during a continuous period of exercise. The first subject investigated is whether the full potential of the anaerobic capacity remains available for exploitation during extended running. Following the work of Margaria (1976) and others, the mathematical models of Lloyd (1967), Ward-Smith (1985), Di Prampero et al. (1993) and Ward-Smith and Mobey (1995) all incorporate a constant value for the amount of energy converted anaerobically during middle- and long-distance track running. In contrast, some scientists, including Peronnet and Thibault (1989), have been persuaded by the work of Gollnick and Hermansen (1973) who suggested that there is a decline in energy from anaerobic sources with increased running distance. The relationship between anaerobic energy conversion and running time will be tested in the present analysis of running data. The second topic to be studied in detail is how long the maximum aerobic power can be sustained. Several mathematical models of middle- and long-distance track running (Ward-Smith, 1985; Di Prampero et al., 1993; Ward-Smith and Mobey, 1995) assume that the maximum sustainable aerobic power is independent of running time.

In contrast, Peronnet and Thibault (1989) have introduced a factor which seeks to account for the long-term decline of aerobic power. They sub-divided their analysis of running performance into two parts. For running times less than \( T_{\text{MAP}} \), the maximum sustainable aerobic power was taken as constant; for running times greater than \( T_{\text{MAP}} \) a maximum sustainable aerobic power which diminished with time was used. It is important to know the relationship between maximum sustainable aerobic power and running time, not only for an improved understanding of the bioenergetics of running, but also for physiological, coaching and dietary reasons.

The present paper investigates these two aspects of running by focusing attention on world record performances over the range of distances from 1500 to 10,000 m. This particular range has been selected because: (i) running times are sufficiently large for the initial build-up of aerobic power to have been completed and power levels to have become independent of the transitory starting phase, and (ii) following the work of Newsholme et al. (1992), by appropriate training and dietary practice, there is the possibility that elite athletes might be able to ensure there is sufficient glycogen available for aerobic conversion, so making the contribution of body fat small or negligible over these distances.

2. Materials and methods

In this paper, physiological data are determined from an analysis of world running records. For optimum performance, running in middle- and long-distance track events is on a knife-edge. Insufficient demands on aerobic metabolism lead to under-performance. When aerobic metabolism is fully established but is incapable of meeting the power required to sustain the running speed, the deficit must be met by oxygen-independent glycolysis. This must be done with considerable precision, as an excessive demand will lead to proton accumulation or to glycogen depletion, either of which will seriously diminish performance. We may reasonably assume that, when a world record is broken, both the aerobic and anaerobic metabolisms are optimally utilised.

The energy \( C^* \) released by chemical conversion in the muscles must ultimately be accounted for either in the form of external work \( W^* \) expended on the centre of mass of the runner, or as mechanical energy degraded into heat, \( H^* \). The asterisk (*) indicates that energy terms are evaluated per unit body mass. The mathematical model can be simplified by ignoring, on order of magnitude grounds and with insignificant loss of accuracy, small-scale cyclical variations in energy levels associated with the stride pattern. The energy balance is then

\[
C^* = H^* + W^*,
\]

where \( H^* \) and \( W^* \) are composed of contributions

\[
H^* = H_1^* + H_2^* \quad \text{and} \quad W^* = W_1^* + W_2^*.
\]

Following Astrand and Rodahl (1986), Ward-Smith (1985), Di Prampero et al. (1993), and others, the degradation of mechanical energy into thermal energy in running over a distance \( X \) in time \( T \) is given by

\[
H^*_1 = A^*X,
\]

where \( A^* \) is a constant.

The work done against aerodynamic drag, assuming still air conditions, is given by

\[
W_{1}^* = \frac{\rho SC_D}{2m} \int_{0}^{T} v^3 \, dt = K^* \int_{0}^{T} v^3 \, dt,
\]

where \( \rho \) is air density, \( S \) is body projected frontal area, \( C_D \) is drag coefficient, \( m \) is body mass, \( v \) is the velocity of the athlete, and \( K^* \) is defined by

\[
K^* = \frac{\rho SC_D}{2m}.
\]

For optimum performance, middle- and long-distance events are run at an essentially even pace, and to a good approximation, we may write

\[
v = V_{av} = \frac{X}{T},
\]

so that \( W_{1}^* \) may be written

\[
W_{1}^* = K^* V_{av}^3 T.
\]
Two remaining terms complete the overall energy balance:

(i) the energy transformed to support basal metabolic activity, \( H_f^s = B^* T \)

(ii) the energy supplied to provide kinetic energy per unit body mass, \( W_s^2 = V_2^2 / 2 \)

There are separate contributions to the chemical energy term from the aerobic and anaerobic mechanisms. Thus,

\[
C^* = C_{an} + C_{aer}.
\]

Substitution for \( H^* = H_f^s + H_u^s \) and \( W^* = W_f^s + W_u^s \) in Eq. (1) and combining the result with Eq. (7) yields the overall energy balance

\[
C_{aer}^* + C_{an}^* = B^* T + A^* X + K^* V_{av}^3 T + V_{av}^2 / 2.
\]

The quantity \( V_{adj} \) is now introduced, defined from the relationship

\[
V_{adj} = V_{av} + A^* - C_{an}^* / A^* T + K^* V_{av}^3 / A^* T + V_{av}^2 / 2 A^* T.
\]

Substitution for \( V_{adj} \) in the energy balance yields

\[
C_{aer}^* = C_{aer}^* / A^* T.
\]

Combination of Eqs. (10) and (13) gives

\[
R_S^* = \frac{\lambda A^* T}{(T - 1)} V_{adj}.
\]

Writing the energy equation in this form provides a particularly clear insight as to whether \( R_S^* \) remains constant or declines over the distances under consideration.

We shall now investigate track statistics on the performance of elite male athletes running over middle-distances and analyse them according to the theoretical model set out above. Current world records are given by Wyse (1997).

To determine \( R_S^* \) from Eqs. (9) and (14), values are required for the variables \( A^*, B^*, C_{an}, K^* \) and \( \lambda \). A representative value of \( B^* = 1.35 \text{ W/kg} \) was taken. For male sprinters, \( K^* \) is close to 0.0029 m\(^{-1}\) (Ward-Smith, 1999). Now, to a good approximation, \( K^* \propto S/m \propto 1/L \), where \( L \) is a representative length. It is appropriate to use a rather higher value for \( K^* \), say 0.0031 m\(^{-1}\), for middle- and long-distance runners, as on average they are of slighter build than sprinters. The values of the remaining three variables \( A^*, C_{an}, \) and \( \lambda \) are evaluated with reference to the minimum r.m.s. error resulting from two values of \( R_S^* \), one deduced from Eq. (14), denoted by \( (R_{S_{\text{track}}}^*) \), the other derived from the correlation equation to be discussed, denoted by \( (R_{S_{\text{calc}}}^*) \).

The first relationship to be tested is the assumption that, for all of the race distances analysed, the amount of energy converted anaerobically is independent of running time or race distance. Thus, we write simply

\[
C_{an}^* = E_0^*,
\]

where \( E_0^* \) is the anaerobic capacity and is constant.

A two-equation model of the maximum sustainable aerobic power is investigated, given by

\[
T < T_{MAP} \quad (R_{S_{\text{calc}}}^*) = R_{S_{\text{max}}},
\]

\[
T > T_{MAP} \quad (R_{S_{\text{calc}}}^*) = R_{S_{\text{max}}} \exp(-\psi(T - T_{MAP})),
\]

where \( R_{S_{\text{max}}} \) is the maximal aerobic power, \( \psi \) is a parameter governing the decline in sustainable aerobic power and, consistent with the work of Peronnet and Thibault (1989), a value \( T_{MAP} = 420 \text{ s} \) is used.

3. Results

The present analysis demonstrates convincingly that, in establishing world records for middle- and long-distance track events, the amount of energy converted anaerobically is independent of race distance (Table 1). It is also demonstrated that the aerobic power remains constant for an initial period but then declines. In column 5 of Table 1 the value of \( (R_{S_{\text{track}}}^*) \), evaluated using Eq. (14), is given; the corresponding value calculated from Eq. (16)
is given in column 6. The percentage error, \( e \), for each data point is shown in column 7, and is calculated as

\[ e \% = \frac{(R^*_S)_{\text{track}} - (R^*_S)_{\text{calc}}}{(R^*_S)_{\text{calc}}} \times 100. \]  

(17)

With \( T_{\text{MAP}} = 420 \text{ s} \), substituting the values \( R^*_{\text{max}} = 27.1 \text{ W/kg} \) and \( \psi = 37 \times 10^{-6} \text{ s}^{-1} \) in Eq. (16) yielded an r.m.s. error of 0.42%, with an average error of 0.003%. Overall, the data display a very impressive internal consistency. The data derived in Table 1 have been used to calculate predicted running times, and these are set out in Table 2. It is evident that the poorest agreement is over 2000 m, the distance least subject to competition. Even so, the data are correlated within a tolerance band of ±0.75%.

Numerous check calculations were undertaken. Setting \( \psi = 0 \) and \( T_{\text{MAP}} = 0 \) in Eq. (16) is equivalent to assuming the aerobic power is independent of race distance from 1500 to 10,000 m. The best correlations yielded an r.m.s. error exceeding 1%, and confirmed the superiority of Eqs. (16a) and (16b), indicating that the aerobic power remains constant for an initial period but then declines.

Calculations were also undertaken to test different assumptions for a declining contribution from anaerobic energy conversion with increasing race distance. With the assumption that \( C_{\text{an}} \) declines linearly with time the r.m.s. error increased. Compelling evidence that the energy from anaerobic metabolism is independent of race distance came when the relations proposed by Peronnet and Thibault (1989) were tested. First, using their values of \( A = 1658 \text{ J/kg}, f = -0.233 \) and \( k_2 = 20 \text{ s}^{-1} \), an r.m.s error exceeding 1% was obtained. The optimum correlation using their relations was obtained with \( A = 1570 \text{ J/kg}, f = 0 \) and \( k_2 = 1/0.033 \). For these values, the Peronnet and Thibault relations effectively reduce to the present formulation.

4. Discussion

That the foregoing analysis is highly successful can be demonstrated by comparing the present results with the outcomes of earlier analyses. The analysis of Ward-Smith (1985) predicted running times within a tolerance band of ±1.5%, whilst the results of Peronnet and Thibault (1989) are within a ±2.3% band. By applying a more focused treatment the present analysis correlates data within a much smaller tolerance band of ±0.75%.

In setting world records the amount of anaerobic energy converted has been shown to be independent of race distance (Table 1). For events at 1500 m and beyond, average running speeds are at levels determined mainly by aerobic metabolism. Until aerobic metabolism is in place, oxygen-independent glycolysis remains the principal source of energy, producing lactate and protons. If the protons are allowed to accumulate, the pH falls to a level where muscle function rapidly declines. The body has a mechanism to remove protons by combining them chemically with a buffer. Within the muscles there is only a limited capacity for buffering. Removal of the protons from the muscle into the blood system exposes the protons to a much more extensive buffering system. The present analysis demonstrates that an athlete underachieves if full use is not made of the buffering capacity within the body. For optimum performance the buffering capacity left unused during the phase of oxygen build-up must be used during the later stages of the race. This is done by setting the mean running speed at a level which permits the power provided by maximal aerobic metabolism to be supplemented by a small amount of oxygen-independent glycolysis, thereby allowing the total energy corresponding to the buffering capacity of the body to be utilised.

The findings of Peronnet and Thibault (1989) that a two-equation model best represents the maximum
sustainable aerobic power, \( R_a \) are supported. For \( T < T_{MAP} \), \( R_a \) is constant and equal to the maximal aerobic power. For \( T > T_{MAP} \), the maximum sustainable aerobic power declines below the maximal aerobic power, being about 4.5% down over 10,000 m. These results indicate that in establishing current world records athletes did not rely solely on glycogen as the source of aerobic metabolism at 5000 and 10,000 m; limited use was made of free fatty acids.

In the present analysis the anaerobic capacity is evaluated as 1570 J/kg. This result compares with the following figures from earlier work: 1683 J/kg (Ward-Smith, 1985), 1658 J/kg (Peronnet and Thibault, 1989), 1430 J/kg (Di Prampero et al., 1993). A figure of 2443 J/kg derived by Ingen Schenau et al. (1991) seems unrealistically high.

The value for maximal aerobic power derived in the present study is 27.1 W/kg. Ward-Smith (1985), using Olympic results over the years from 1969 to 1976, analysed distances from 100 to 10,000 m and obtained a constant value of 23.5 W/kg above resting, corresponding to 24.85 W/kg when the basal metabolic power is included. Perronet and Thibault (1989) used 1987 world records for distances from 60 to 42,195 m (the marathon), and obtained 29.1 W/kg. Concentrating on the range 800–5000 m, Di Prampero et al. (1993) showed that a constant value of 25.7 W/kg above resting, which equates to 27.05 W/kg if an allowance of 1.35 W/kg is added to account for the basal metabolic power, was in good agreement with the existing world records of 1989. The figure of 27.05 W/kg is in very close accord with the 27.1 W/kg found in the present analysis. If 1 ml O\(_2\) is taken as equivalent to 20.9 J, then 1 W/kg is equivalent to 2.871 ml O\(_2\)/kg/min. Using this conversion factor, the values of \( R_{max}^a \) derived in the present analysis, 27.1 W/kg, corresponds to a maximum oxygen consumption of 77.8 ml O\(_2\)/kg/min.

There is a general accord in the literature concerning the energy cost of running. The value of 3.89 J/m/kg derived in the present analysis compares well with previous figures: 3.90 J/m/kg (Ward-Smith, 1985), 3.86 J/m/kg (Peronnet and Thibault, 1989), 3.79 J/m/kg (Di Prampero et al., 1993).

Finally, the present value of \( \lambda = 0.033 \text{s}^{-1} \) compares with the following figures: 0.03 s\(^{-1}\) (Ward-Smith, 1985), 0.033 s\(^{-1}\) (Peronnet and Thibault, 1989), 0.0384 s\(^{-1}\) (Ingen Schenau et al., 1991), and 0.1 s\(^{-1}\) (Di Prampero et al., 1993). The latter figure is based on earlier work and appears rather high; recent results seem to be converging on a value between about 0.033 and 0.039 s\(^{-1}\).

In summary, a focused analysis of world-record data for distances from 1500 to 10,000 m, based on whole-body bioenergetics, has yielded new quantitative information on the main physiological properties relevant to the running performance of elite male athletes. The analysis supports the result of Peronnet and Thibault (1989) that the maximum sustainable aerobic power is constant for running times below about 420 s, but then decreases progressively. The present study shows it declines by some 4.5% below the maximum for the world record time over the distance of 10,000 m. Excellent correlations of world records have been obtained demonstrating that the anaerobic energy utilised over distances from 1500 to 10,000 m is constant and independent of running distance. This result is consistent with the view that the full potential of the anaerobic capacity is available for conversion during extended periods of running, and is in contrast to the views of Gollnick and Hermansen (1973) and Peronnet and Thibault (1989) that the energy contribution from anaerobic metabolism decreases with race distance. For elite male athletes, the maximum sustainable aerobic power was evaluated as 27.1 W/kg and the anaerobic capacity was found to be 1570 J/kg.

References


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