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ORIGINAL ARTICLE

Estimation of running endurance by means of empirical models: A preliminary study

Estimation de l'endurance en course à pied par des modèles empiriques: étude préliminaire

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Running

Summary
Purpose. — The relationships between distance (D_{lim}), speed (S) and exhaustion time (t_{lim}) can be described by different empirical models: power laws ($D_{lim} = kt_{lim}{}^{g}$, and $S = kt_{lim}{}^{(g-1)}$ in Kennelly's model); critical speed (S_{Crit}) ($D_{lim} = a + S_{Crit}\ t_{lim}$) and logarithmic model ($S = 1—E$*$\ln t_{lim}$ in Péronnet—Thibault model).
Methods. — These models have been applied to the performance of nine physical education students. In the first session, they performed the Montreal Track Test whose speed at the last stage (sMTT) is assumed to correspond to maximal aerobic speed. Thereafter, they performed 3 exhausting running exercises at 90, 100 and 110% sMTT, in different sessions with randomized order. The values of g and k were computed as (g_1, k_1) from t_{lim} at 90 (t_{lim90}), 100 (t_{lim100}) and 110% sMTT (g_1, k_1) and also from t_{lim90} and t_{lim100} (k_2, g_2). The values of S_{Crit} were normalized to sMTT.
Results. — Significant correlations ($r > 0.999$) of the relationships between the logarithms of D_{lim} and t_{lim} were observed. S_{Crit} was not significantly correlated with g_1, g_2 and E. In contrast, the correlations between the individual values of g_1, g_2 and E were highly significant.
Conclusion. — The high relationship between the logarithms of D_{lim} and t_{lim} suggested that power laws can be applied to subjects not-specialized in endurance. However, further studies with different protocols are necessary to determine if the power-law model is more accurate and useful than the logarithmic model in subjects who are not specialized in endurance.
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MOTS CLÉS
Vitesse critique ;
Modèle de Kennelly ;
Lois de puissance ;
Modèle de Péronnet—Thibault ;
Course à pied

Résumé

Objectif. — Les relations entre la distance (D_{lim}), la vitesse (S) et le temps d'épuisement (t_{lim}) peuvent être décrites par différents modèles empiriques: lois de puissance ($D_{lim} = kt_{lim}{}^{g}$ et $S = kt_{lim}{}^{(g-1)}$, model de Kennelly), vitesse critique (S_{Crit}) ($D_{lim} = a + S_{Crit}\ t_{lim}$) et modèle logarithmique ($S = 1 - E^{*}\ln t_{lim}$, modèle de Péronnet—Thibault).

Méthodes. — Ces modèles ont été appliqués aux performances de 9 étudiants en éducation physique. Dans la première séance ils réalisèrent le « Montreal Track Test » dont la vitesse au dernier palier (sMTT) est proche de la vitesse maximale aérobie. Ensuite, ils réalisèrent 3 exercices de course jusqu'épuisement à 90, 100 et 110 % sMTT, dans différentes sessions dans un ordre randomisé. Les valeurs de g et k furent calculées à partir de t_{lim} à 90 (t_{lim90}), 100 (t_{lim100}) et 110 % sMTT (g_1, k_1) et aussi uniquement à partir de t_{lim90} and t_{lim100} (k_2, g_2). Les valeurs de S_{Crit} furent rapportées à sMTT.

Résultats. — Des correlations significatives ($r > 0{,}999$) entre les logarithmes de D_{lim} et t_{lim} furent constatées. S_{Crit} n'était pas significativement corrélé avec g_1, g_2 et E. Au contraire, les corrélations entre les valeurs individuelles de g_1, g_2 et E étaient très significatives.

Conclusion. — Les correlations élevées entre les logarithmes de D_{lim} et t_{lim} suggèrent que les lois de puissance peuvent être appliquées aux sujets non spécialisés en endurance. Cependant, des études ultérieures avec différents protocoles sont nécessaires pour déterminer si le modèle lois-de-puissance est plus précis et utile que le modèle logarithmique chez des sujets non spécialisés en endurance.

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Introduction

In addition to biomechanical and biochemical models [1—8] different empirical models of the running performances have been proposed: power laws, hyperbolic and logarithmic models. In 1966, Ettema [9] applied the concept of critical power [10] to world records in running:

$$D_{lim} = a + bt_{lim}$$

Where t_{lim} corresponded to the world record for a given distance (D_{lim}). Slope b was considered as a critical speed (S_{Crit}) equivalent to critical power:

$$D_{lim} = a + S_{Crit}\, t_{lim}$$

In 1981, the interest for the concept of critical power or critical speed was renewed after a study on the application of the critical power to cycling exercises [11]. Nowadays, the critical-speed model is probably the most studied although the D_{lim}—t_{lim} relationship is not linear. Indeed, the slope of the D_{lim}—t_{lim} relationship depends on the range of t_{lim} and is higher for sprint races than for endurance races [9]. Many years before (1906), Kennelly had proposed power laws [12] for the relationhip between speed (S), distance (D) and time (t) in a descriptive model for world running records:

$$D = kt^{g}$$

$$S = kt^{g-1}$$

where g is an exponent.

As in the study by Kennelly, power laws have also recently been applied to world records [13—15]. Exponent g is a dimensionless parameter that can be considered as an endurance index. Indeed, g is close to 1 in elite endurance runners and lower in subjects who are not specialized in endurance running [16—18].

Another not-linear empirical model (logarithmic model) has been proposed for the relationship between speed (S) and t_{lim} for running exercises beyond 7 min by Péronnet and Thibault [1]:

$$S/MAS = 100 - E\ln(t_{lim}/t_{MAS})$$

Where E is an endurance index and t_{MAS} was assumed to be equal to 7 min. However, the value of t_{MAS} is debated [2].

The models of Kennelly [12—15] and Péronnet—Thibault [1] have already been tested in elite athletes. Moreover, these two models were highly correlated in a study on elite athletes [16]. Both the logarithmic model and Kennelly's model can describe with accuracy [17] the performances of elite endurance runners whose values of g are high (0.90—95). On the other hand, the correlation between g (Kennelly model) and E (Péronnet—Thibault model) could be weak in subjects who are not endurance runners and whose values of g are lower than 0.85 [18]. The present study aimed to compared, the different indices of running endurance (S_{Crit}, g, E) in subjects who are not endurance runners in order to estimate the most useful index.

Materiels and methods

Participants

The D_{lim}—t_{lim} and S—t_{lim} relationships were studied in nine physical-education students (24.7 ± 1.9 years; 75.6 ± 6.5 kg;

1.79 ± 0.05 m). All procedures were explained to them and a written consent document approved by the institutional review board was completed before the procedures were started. The experimental protocol was carried out according to the guidelines of the declaration of Helsinki.

Protocol of running exercises

The running exercises were performed on a 100 m indoor track with cones placed every 12.5 meters. Running speed was imposed by a beeper controlled by a personal computer. The subjects must be within 2 m from the cones at each sound and they were considered as exhausted when they were unable to accelerate to compensate a 2-meter delay. In the first session, MAS was estimated by means of the Montreal Track Test [19] that consists of a graded-test (two-minute stages with speed increments equal to 1 km.h^{-1}) until exhaustion. MAS is assumed to be close to the running speed (sMTT) of the last completed stage. In each of the following sessions, the participants performed an exhausting running exercise at either 90 or 100 or 110% sMTT, in a random order.

Heart rate was recorded during the exercise with a heart rate monitor (Polar RS400, Polar Electro Oy, Kempele, Finland) with a sampling frequency every 5 seconds. The higher value at the end of the exercise has been registred.

Blood lactate was measured using a portable blood lactate analyzer (Lactate Pro, Arkray, Tokyo, Japan). The lactate analyzer was calibrated before each testing session. This blood lactate analyzer has been reported to be reliable and valid [20]. Capillary blood samples (5 µL) were collected from the fingertip of a prewarmed hand for lactate concentration immediately and 2 min after exhaustion. The higher value was taken account. These capillary blood samples were considered as arterialized blood samples.

The rate of perceived exertion (RPE) was recorded immediately at the end of the exercise using the Borg 15-point category scale ranging from 6 (resting state) to 20, (maximal exertion) [21].

Computations and statistics

The values of g and k of the individual power laws were computed form the linear regression between the logarithms of D_{lim} and t_{lim}:

$$D_{lim} = kt_{lim}{}^{g}$$

$$\ln(D_{lim}) = \ln(k) + g\ln(t_{lim})$$

$$Y = \ln(D_{lim})$$

$$X = \ln(t_{lim})$$

$$Y = m + nX$$

where $k = \exp(\ln(k)) = \exp(m)$ and $g = n$.

The values of k and g (k_1 and g_1) were computed from the values of D_{lim} corresponding to t_{lim} at 90 (t_{lim90}), 100 (t_{lim100}) and 110% sMTT. To verify that the $D_{lim}-t_{lim}$ power law is an accurate model, k and g were also computed (k_2 and g_2) from the values of D_{lim} corresponding to t_{lim} at 90 (t_{lim90}) and 100 (t_{lim100}) without taking into account D_{lim110} and t_{lim110}. If the individual power laws computed from D_{lim} and t_{lim} are perfect, the individual values of k_1 and g_1 should be equal k_2 and g_2, respectively.

S_{Crit} was estimated by computing the regression between D_{lim} and t_{lim}:

$$D_{lim} = a + bt_{lim}$$

Where b was equal to S_{Crit}.

Parameter E of the logarithmic model proposed by Péronnet and Thibault [1] was adaptated to sMTT:

$$S/sMTT = 1 - E\ln(t_{lim}/t_{limsMTT}) = 1 - E\ln(t_{lim}/t_{lim100})$$

The value of t_{lim110} was not used in the computation of E as this model is used to describe the S-t_{lim} relationship for $t_{lim} \geq t_{MAS}$.

$$S_{90}/sMTT = 1 - E\ln(t_{lim90}/t_{limsMTT}) = 0.90$$

Therefore, E was equal to:

$$E = (1-0.90)/\ln(t_{lim90}/t_{lim100}) = 0.1/\ln(t_{lim90}/t_{lim100})$$

The individual differences between g_1 and g_2 were computed as following:

$$\text{Differencein\%} = 200|g_1 - g_2|/(g_1 + g_2)$$

The individual differences between k_1 and k_2 was computed with the same method.

Statistics

Given the small number of participants, a Wilcoxon test for paired samples was used to analyze statistical differences. Wilcoxon tests and linear regressions were carried out using Sigma—Stat software (Systat Software, Germany).

Results

The average values of t_{lim}, HR, [Lact] and RPE at 90, 100 and 110% sMTT are presented in Table 1. The difference between RPE at 100 and 110% sMTT was the only significant difference ($P = 0.008$) for HR, [Lact] and RPE.

Power law model

The correlation coefficients of the individual regressions between $\ln(D_{lim})$ and $\ln(t_{lim})$ were high ($r \geq 0.999$). The mean values of exponents g_1 and g_2 were not significantly different and the individual absolute differences between g_1 and g_2 were moderate ($4.8 \pm 4.1\%$). The mean values of k_1 and k_2

Table 1 Mean values ± SD of t_{lim}, heart rate, blood lactate and rate of perceived exertion (RPE) for the 3 running velocities (90, 100 and 110% sMTT).

	90% sMTT	100% sMTT	110% sMTT
t_{lim} (s)	624 ± 127	338 ± 61	217 ± 37
Heart rate (bpm)	190 ± 8.3	190 ± 7.8	190 ± 11.2
Lactate (mmol.L^{-1})	12.7 ± 1.8	12.6 ± 1.54	13.7 ± 1.9
RPE	15.7 ± 2.3	15.3 ± 1.5	16.7 ± 1.7

Table 2 Individual values, mean (M) and standard deviation (SD) of the parameters of the different models, computed either from t_{lim90}, t_{lim100} and t_{lim110} (k_1, g_1 and S_{Crit}.) or from t_{lim90} and t_{lim100} (k_2, g_2 and E). The values of S_{Crit} are normalized to sMTT.

	sMTT	Power laws				Logarithmic	Hyperbolic
Subject	km.h^{-1}	k_1	g_1	k_2	g_2	E	S_{Crit}
1	16.00	9.43	0.872	7.8	0.902	0.093	0.852
2	14.50	23.9	0.701	19.8	0.731	0.255	0.752
3	16.75	24.7	0.714	40.2	0.634	0.348	0.836
4	15.50	12.2	0.826	21.0	0.740	0.247	0.808
5	16.50	12.5	0.826	11.1	0.844	0.148	0.860
6	13.75	10.8	0.825	8.0	0.871	0.122	0.874
7	15.75	12.0	0.832	12.7	0.823	0.168	0.806
8	14.00	11.4	0.810	9.7	0.837	0.155	0.730
9	14.00	11.0	0.816	10.6	0.821	0.170	0.875
M	15.19	14.2	0.802	15.7	0.800	0.190	0.821
SD	1.15	5.8	0.057	10.4	0.083	0.079	0.052

(Table 2) were not significantly different but the individual absolute differences between k_1 and k_2 were not negligible (22.8 ± 17.7%). As k_1 and k_2, exponents g_1 and g_2 were significantly correlated:

$$k_2 = -5.387 + 1.481 k_1 r = 0.828; P = 0.006$$

$$g_2 = -0.176 + 1.216\, g_1 r = 0.826; P = 0.006$$

Logarithmic model

Parameter E was significantly correlated with g_1 (Fig. 1, black dots):

$$E = -1.116 + 1.154\, g_1 r = 0.826; P = 0.006$$

The relationship between the invidual values of E and g_2 was perfectly linear (Fig. 1, empty circles):

$$E = 0.949 – 0.949\, g_2 r = 1$$

Critical speeds

The average value of S_{Crit}/sMTT (0.821 ± 0.052, Table 1) was not significantly different ($P > 0373$) from g_1 (0.802 ± 0.057) and g_2 (0.800 ± 0.083). However, the individual values of

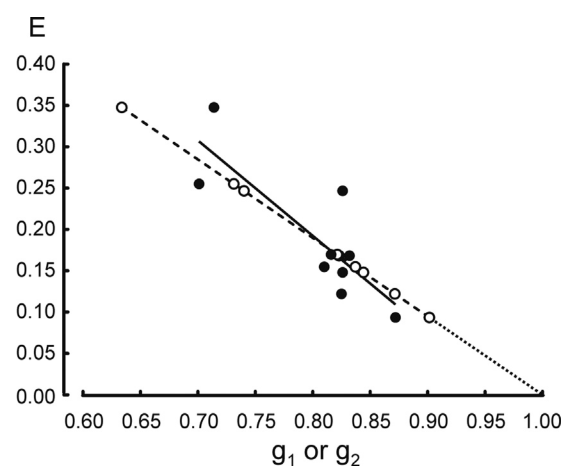

Figure 1 Relationship between either E and g_1 (black dots, solid line) or E and g_2 (empty circles, dashed line).

S_{Crit}/sMTT were not significantly correlated with the individual values of g_1, g_2 and E:

$$S_{CRIT}/sMTT = 0.531 + 0.361\, g_1 r = 0.391; P = 0.298$$

$$S_{CRIT}/sMTT = 0.689 + 0.165\, g_2 r = 0.263; P = 0.494$$

$$S_{CRIT}/sMTT = 0.854 – 0.174 E r = 0,263; P = 0.494$$

Discussion

The results of the present study suggested that both models of Kennely and Péronnet—Thibault can be applied to subjects who are not endurance runners. Indeed the parameter E of the Péronnet—Thibault model was significantly correlated with the parameters g_1 and g_2 of the Kennelly model. Similarly, the value of S_{Crit}/sMTT was not significantly different from g_1 and g_2. The differences between the individual values of g_1 and g_2 were moderate and the correlation between g_1 and g_2 were significant. On the other hand, the individual differences between k_1 and k_2 were not negligible although the mean values of k_1 and k_2 were not significantly different.

In a previous study [18] value of S_{Crit} was close to the value of g for the usual range of t_{lim} between 3—15 min, as in the present study. Similarly, the average value of S_{Crit}/sMTT was not significantly different from g_1 and g_2 in the present study. But the correlations between the individual values of S_{Crit} and g_1, g_2 or E were not significant probably because the range of S_{Crit} was relatively small (from 0.730 to 0.875, Table 1) and S_{Crit} depends on t_{lim} [9]. In theory, S_{Crit} represents the fastest speed that can be maintained a very long time. However, on a treadmill, the subjects are generally only able to maintain S_{Crit} for less than 30 min and the running velocities that could be maintained for 60 minutes on a treadmill are largely overestimated by S_{Crit} [22]. An overestimation should be higher in subject whose D_{lim}—t_{lim} relationship is more curved. Maximal lactate steady state is usually sustainable for 30 to 60 min [23—25]. In a study on endurance runners [26], the running speed at lactate steady-state (4.80 m.s^{-1}), estimated according to the protocol proposed by Chassain [27], was significantly correlated (r = 0.97) and not significantly different from the value of S_{Crit} (4.83 m.s^{-1}), excepted in one subject. In this latter study, the highest individual values of t_{lim} were longer than 30 min.

The curvature of the D_{lim}—t_{lim} relationship depends on the decrease in the fraction of maximal aerobic metabolism that can be sustained during long lasting exercises. The D_{lim}—t_{lim} relationship is almost linear and g is close to 1 in elite endurance runners [16,18]. The value of g_1 was lower (0.802) for the subjects of the present study who were not specialized in endurance exercises. The results of the present study suggest that the Kennelly's model could describe the running performances of subjects who are not specialized in endurance running because: i) the correlation coefficient between ln(D_{lim}) and ln(t_{lim}) were high ($\geq$ 0.999); ii) the mean values of g_1 and g_2 were not significantly different and the individual values of g_1 and g_2 were significantly correlated. However, the individual differences between the parameters of the power laws in Tables 1 and 2 were not negligible (4.8% for the differences between g_1 and g_2 and 22.8% for the difference between k_1 and k_2). Parameter k whose difference between k_1 and k_2 is important is less interesting than parameter g that is an endurance index. The difference between g_1 and g_2 could be the expression of the lack of precision of the Kennelly's model and/or the result of submaximal performances.

The relationship between E and g_2 (Fig. 1, empty circle) was perfectly linear (r = 1). But it can be mathematically demonstrated (Appendix 1) that the relationship between the individual values of E and g is perfectly linear when E and g are computed from $t_{lim\ 100}$ and only one another values of t_{lim} corresponding to the same fraction of sMTT (or MAS). This perfect linear relationship between E and g_2 also explained that the coefficients of correlation were the same (r = 0.263) for the relationships between S_{Crit}/sMTT and either E or g_2. The results of the protocol of the present investigation suggest the possibility of the application of Kennelly's model in subjects who are not elite endurance runners. Moreover, the results obtained with the present protocol showed that g_1 was highly correlated with E (Fig. 1). However, the accuracy of the Péronnet—Thibault model could not be evaluated with the protocol used in the present study because E was computed with only two values of t_{lim} (t_{lim100} and t_{lim90}).

In the future, it would be interesting to test what model (Kennelly or Péronnet—Thibault) is the most accurate by studying the running performances with other experimental protocols including at least 3 speeds, lower or equal to 100% sMTT. For example, either a 0.80—0.90-100% sMTT protocol or a 0.90—0.95-100% sMTT protocol. Moreover, a protocol with repetitions of the exhausting exercises at each running speed would probably improve the validity of the performances. After this future study, endurance could be evaluated with the endurance parameter of the best model (E or g) applied to the results of a simplified protocol consisting of only 2 running speeds. Indeed, critical speed, Kennelly model and Péronnet—Thibault model can be computed with only two values of t_{lim}. Such a protocol would include running speeds at 85 and 100% sMTT in subjects who are not endurance runners. The aim of the slower running exercise (85% sMTT) would be to reach a value of t_{lim} al least between 20 and 40 min. In these subjects it is likely that S_{Crit} would be closer to the running speed at lactate steady-state with such a protocol including a lower speed (85% sMTT) and excluding speeds higher than 100% sMTT. In endurance runners, a protocol including running speeds at 90 and 100% sMTT would be performed. In elite endurance runners, a 95% sMTT speed would probably be preferable to a 90% running speed. Morever, several repetitions at each speed would be performed to improve the validity of the data.

Conclusion

Parameters g_1, g_2 and E were significantly correlated. Therefore, the results of the present study suggested that Kennelly's model can be applied to the individual performances of subjects who are not elite endurance runners. However, the data of the present study did not enable to decide if the model of Kennelly [12] is more accurate and more useful than the logarithmic model proposed by Péronnet and Thibault [1]. Therefore, further studies with different protocols are necessary for the confirmation of the results of the present study and the comparison of the accuracy of the power law and logarithmic models.

Disclosure of interest

The authors declare that they have no competing interest.

Appendix A. Appendix A

For t_{lim100} and t_{lim90} the S-t_{lim} equation in the power law model is:

$S_{100}/sMTT = k\ t_{lim100}{}^{(g-1)}/sMTT = 1$

$S_{90}/sMTT = k\ t_{lim90}{}^{(g-1)}/sMTT = 0.9$

Therefore:

$(t_{lim90}/t_{lim100})^{(g-1)} = 0.9 \ln(t_{lim90}/t_{lim100})^{(g-1)} = (g-1) \ln(t_{lim90}/t_{lim100}) = \ln(0.9) \ln(t_{lim90}/t_{lim100}) = \ln(0.9)/(g-1)$

As $E = 0.1/\ln(t_{lim90}/t_{lim100})$ and $\ln(0.9) = -0.1054$

$E = 0.1\ (g-1)/(-0.1054) = -0.949\,g + 0.949$

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