Relationship Between Run Times to Exhaustion at 90, 100, 120, and 140% of $v\dot{V}O_2max$ and Velocity Expressed Relatively to Critical Velocity and Maximal Velocity

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The aim of the present study was to explain the inter-individual variability in running time to exhaustion (tlim) when running speed was expressed as a percentage of the velocity, associated with maximal oxygen uptake ($v\dot{V}O_2max$). Indeed for the same percentage of $v\dot{V}O_2max$ the anaerobic contribution to energy supply is different and could be dependent on the critical velocity (Cv) and also on the maximal running velocity (v_{max}). Ten subjects ran four tlim at 90, 100, 120, and 140% of $v\dot{V}O_2max$; mean and standard deviation for tlim were 839 ± 236 s, 357 ± 110 s, 122 ± 27 s, and 65 ± 17s, respectively. Each velocity was then expressed 1) as a percentage of the difference between $v\dot{V}O_2max$ and Cv (%AeSR); 2) as a percentage of the difference between v_{max} and Cv (%MSR); 3) as a percentage of the difference between v_{max} and $v\dot{V}O_2max$ (%AnSR). Highest correlations were found between tlim90 and tlim100 and velocity expressed as %MSR ($r = -0.82$, $p < 0.01$ and $r = -0.75$, $p < 0.01$), and between tlim120 and tlim140 and velocity expressed as %AnSR ($r = -0.83$, $p < 0.01$ and $r = -0.94$, $p < 0.001$). These results show that the same intensity relative to aerobic contribution did not represent the same absolute intensity for all and could partly explain variability in tlim. Therefore expressing intensity as a percentage of MSR for sub-maximal and maximal velocities and as a percentage of AnSR for supra-maximal velocities allows individual differences in anaerobic work capacity to be taken into account and running times to exhaustion to be predicted accurately.

Key words: Field tests, running, maximal velocity, critical velocity, maximal aerobic velocity, time to exhaustion.

Introduction

For running training the determination of running velocity and duration of exercise is a decisive factor in training efficiency. Many researchers and coaches use training velocities expressed as percentages of the velocity associated with maximal oxygen uptake ($\dot{V}O_2max$) [3,8], and some of them proposed individualizing duration of exercise with regard to running time to exhaustion [4]. However, numerous studies have reported a great inter-individual variability in running time to exhaustion (tlim) [6,11,12,15]. Some authors have tried to explain this variability by taking into account the difference between anaerobic abilities of the subjects. Hill and Rowell [10] showed that only 26% of the variability in time to exhaustion at $v\dot{V}O_2max$ (tlim100) could be explained by differences in anaerobic capacity as estimated by oxygen deficit while 44% of this variability could be explained by intra-individual differences in anaerobic threshold. For supra-maximal velocities Camus et al. [7] showed that inter-individual differences in tlim were diminished by subtracting the maximal aerobic power from the energy cost of exercise per unit of time and concluded that tlim was related to the anaerobic component in energy supply. Their results showed that tlim was independent of $\dot{V}O_2max$, but they failed to explain variability of tlim100. To the same extent Barnett et al. [1] showed reduced variabilities in tlim by expressing supra-maximal intensities with regard to $\dot{V}O_2max$ and to the mean anaerobic scope, which account for different aerobic and anaerobic abilities. However, these different studies were not designed to explain variability in tlim at velocities ranging from sub-maximal to supra-maximal. To modelize tlim over this range of intensities, Morton [18] had proposed a 3-parameter mathematical model which takes into account critical power and maximal power:

$$\mathrm{tlim} = \frac{AWC}{P - CP} + \frac{AWC}{CP - Pmax} \qquad \text{(equation 1)}$$

where AWC represents the anaerobic work capacity (i.e. the total work that can be performed by the body's limited energy resources [18]) and CP the critical power (i.e. the maximal power which can be sustained over a long period of time without fatigue). Based on the model of Ettema [9], equation 1 could be modified as follows for running events:

$$\mathrm{tlim} = \frac{ADC}{v - Cv} + \frac{ADC}{Cv - V_{max}} \qquad \text{(equation 2)}$$

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where ADC is anaerobic distance capacity (i.e. distance run using anaerobic resources) and Cv the critical velocity (i.e. the velocity that can be sustained over a long period of time without fatigue).

From this last equation it could be postulated that running intensity depends not only on v$\dot{V}O_2$max but also on ADC, v-Cv, and Cv-v_{max}.

Therefore this study was designed to test the hypothesis that time to exhaustion, for velocities between critical velocity to maximal velocity (90%, 100%, 120%, and 140% of v$\dot{V}O_2$max), could be best related with velocities when expressed as a percentage of the difference between v_{max} and Cv. This range was called maximal speed reserve (MSR). Velocities were also expressed, firstly as percentages of the difference between v$\dot{V}O_2$max and Cv for sub-maximal velocities (under v$\dot{V}O_2$max). The latter was called aerobic speed reserve (AeSR). Secondly, velocities were expressed as percentages of the difference between v_{max} and v$\dot{V}O_2$max for supra-maximal velocities (above v$\dot{V}O_2$max); this range was called the anaerobic speed reserve (AnSR) (Fig. **1**).

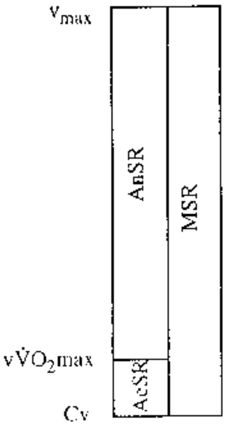

Fig. 1 Representation of the range of speed from critical velocity (Cv) to maximal velocity (V_{max}). The maximal speed reserve (MSR) represents v_{max} minus Cv, the aerobic speed reserve (AeSR) represents v$\dot{V}O_2$max minus Cv, and the anaerobic speed reserve (AnSR) represents v_{max} minus v$\dot{V}O_2$max.

Methods

Subjects

Ten physical education students volunteered to participate in this study and gave their written informed consent. The experimental protocol had previously been reviewed and approved by an Ethics Committee for the Protection of Human Subjects (Région Nord, Pas de Calais, France). The subjects underwent a complete medical examination prior to the experiments. They all trained 2 or 3 times a week in different sports. Their age, body mass, height, and body mass index were 20.8 ± 2.1 years (mean ± SD), 74.4 ± 8.9 kg, 1.81 ± 0.08 m, and 22.6 ± 1.6 kg × m^{-2}, respectively.

Experimental design

Before entering the study, the subjects were familiarized with the exercise procedure and running with an oxygen analyzer. Each subject performed seven tests over 2 weeks with at least 24 hours between two consecutive tests. $\dot{V}O_2$max and v$\dot{V}O_2$max were measured in a preliminary field test session using a progressive and maximal exercise protocol. Running times to exhaustion at 90, 100, 120, and 140% of v$\dot{V}O_2$max (tlim90, tlim100, tlim120, and tlim140) and maximal running velocity (v_{max}) were then measured in a random order. All tests were performed on a 200 m track in an indoor-stadium at the same hour of day. For the incremental test and tlim tests the 200 m track was marked with cones every 25 m. The running velocity was imposed with a tape recorder which indicated by means of a brief sound the moment when the subjects had to pass near a cone to maintain a constant speed. During all tests subjects were verbally encouraged. The test ended with the volitional exhaustion of the subject or when he was unable to run at the selected velocity. Oxygen uptake was measured for the maximal field test and for the tlim90, tlim100, tlim120, and tlim140 tests. Blood lactate measurements were obtained after each test between 2 – 3 min of recovery.

Physiological measurements

During all the tests (except for v_{max}) expired air was analyzed with a portable telemetry system (Cosmed K2, Milan, Italy), allowing the measurement of oxygen consumption and ventilation. During the test the K2 was strapped to each subject with a chest harness. Expired gases were collected every 15 s, and data were transmitted telemetrically to the K2 receiving unit. Before each test the turbine flow-meter was calibrated with a 3 l syringe (Quinton Instruments, Seattle, USA), and the analyzer was calibrated using room air, of which partial pressure of oxygen was assumed to be 20.9% (K2 instructions manual). This device has previously been described and validated [2,14]. Heart rate (HR) was measured with a short range telemetry system (Polar Accurex+, Finland). During the test ambient temperature ranged from 17 to 23 °C. Finger tip blood samples were obtained and analyzed for lactate concentration by a spectrophotometric method (Dr. Lange, Berlin, Germany). Before each test the analyzer was calibrated with solutions of known concentration.

Determination of maximal oxygen uptake and velocity associated to $\dot{V}O_2$max

$\dot{V}O_2$max and v$\dot{V}O_2$max were measured in a preliminary test session using an incremental running field test. The initial velocity was set at 10 km × h^{-1} and was increased by 2 km × h^{-1} every 4 min. The stages were separated by 1 min recovery. $\dot{V}O_2$peak was the mean of $\dot{V}O_2$ over the last minute of the test (four 15 s measurements). The criteria used for $\dot{V}O_2$peak comprised: a plateau in $\dot{V}O_2$ (increase lower than 2.1 ml × kg^{-1} × min^{-1}) despite an increase in running speed, a heart rate close to maximal theoretical heart rate for running events, blood lactate concentration higher than 10 mmol × l^{-1}, and a subjective exhaustion.

The velocity at maximal oxygen uptake (v$\dot{V}O_2$max) was calculated from $\dot{V}O_2$peak and energy cost of running (Cr) according to Lacour et al. [13] and Medbø et al. [17]. Energy cost of running (ml × kg^{-1} × km^{-1}) was calculated as Cr = ($\dot{V}O_2$ – $\dot{V}O_2$ at rest)/v, where $\dot{V}O_2$ was the oxygen consumption (ml × kg^{-1} × h^{-1}) at a selected velocity (v in km × h^{-1}). $\dot{V}O_2$ at rest was set at 5 ml × kg^{-1} × min^{-1}, according to Medbø et al. [17]. The $\dot{V}O_2$ at a selected velocity was the average of the last four measured values delivered per K2 at the end of each stage. v$\dot{V}O_2$max was then calculated as v$\dot{V}O_2$max = ($\dot{V}O_2$peak – $\dot{V}O_2$

at rest)/Cr. The $v\dot{V}O_2max$ values were rounded to the nearest half kilometer.

Constant velocity tests

Subjects performed four constant velocity tests at 90, 100, 120, and 140% of $\dot{V}O_2max$ to measure running times to exhaustion (tlim) and distance limit (dlim).

Critical velocity was calculated using the dlim *versus* tlim relationship as proposed by Ettema [9]: dlim = (Cv × tlim) + ADC, where Cv is the critical velocity ($m \times s^{-1}$) and ADC the anaerobic distance capacity (m).

Determination of accumulated oxygen deficit

During tlim at 120 and 140% of $v\dot{V}O_2max$ accumulated oxygen deficit (AOD) was determined in accordance with the method proposed by Marais et al. [16], adapted from the procedure of Medbø et al. [17]. Briefly the AOD that incurred during the supra-maximal exercises was calculated as the difference between the oxygen demand and oxygen uptake accumulated over the duration of tlim. The oxygen demand was predicted from the linear regression between $\dot{V}O_2$ and velocity determined from the sub-maximal stages of the incremental test. The maximal AOD, measured from tlim120 or tlim140, was retained for statistical analyses.

Maximal running velocity

Maximal running velocity (v_{max}) was measured from an individual 60 m race. The velocity was measured with four photocells (Brower Timing Systems IRE et IRD-T175, Salt Lake City, USA) which were placed at 20, 40, and 60 m. Times were collected telemetrically using a chronometer (Brower Timing Systems CM 705 CR, Salt Lake City, USA). Measured time began when the runner cut the cells' pencil. The height of the photocell was adjusted in order to be cut with the hip of the subjects. The v_{max} was the highest velocity measured over each 20 m interval.

Data analysis

Experimental values are presented as mean ± standard deviation (mean ± SD). The differences between mean experimental measures were analyzed with the Wilcoxon test for paired series. Correlation between the different tlim and physiological variables were calculated. Simple regressions were computed between tlim and velocities in absolute units ($km \times h^{-1}$) and in relative units, i.e. expressed as percentages of v_{max} minus Cv (i.e. maximal speed reserve, MSR), $v\dot{V}O_2max$ minus Cv (i.e. aerobic speed reserve, AeSR), and v_{max} minus $\dot{V}O_2max$ (i.e. anaerobic speed reserve, AnSR). In all statistical analyses the significance threshold was set at $p < 0.05$.

Results

The mean physiological measurements for each test are presented in Table **1**. Maximal $\dot{V}O_2$ and [La] reached in incremental and in tlim tests were not significantly different.

The velocities and tlim measured for the field tests are presented in Table **2**. The coefficients of determination (r^2) of Cv associated with the dlim *versus* tlim relationships were all higher than $r = 0.99$. Large variability was observed in the different tlim as indicated by the coefficients of variation associated with tlim90 (26%), tlim100 (31%), tlim120 (22%), and tlim140 (26%).

Figs. **2**, **3**, and **4** show the relationships between each tlim and the corresponding velocity expressed as percentages of AeSR, MSR, and AnSR. There was no relationship between tlim90, tlim100, tlim120, or tlim140 and the respective velocity when expressed as kilometers per hour. Highest relationships for the different tlim and the respective velocities were found between tlim90 and velocity expressed as a percentage of MSR ($r = -0.82$; $p < 0.05$), tlim100 and velocity expressed as a percentage of MSR ($r = -0.75$; $p < 0.01$), tlim120 and velocity expressed as a percentage of AnSR ($r = -0.83$; $p < 0.01$), and tlim140 and velocity expressed as a percentage of AnSR ($r = -0.94$; $p < 0.001$).

Table **3** shows the correlations between tlim and the different physiological variables. No significant correlation was found between any tlim and $\dot{V}O_2max$. Tlim90 was uncorrelated with any variable. Tlim100, 120, and 140 were significantly correlated with ADC and AOD (except for tlim120).

Discussion

In the present study we assumed that expressing speed related to a specific range of velocities (between Cv and v_{max}) may lead to obtain significant relationships between tlim and running velocity and thus an accurate prediction of these tlim. To test this hypothesis, running paces were expressed as percentages of AeSR, MSR, and AnSR. It was expected that tlim would be best related to the velocity expressed as percentages of MSR.

The main finding from this study was that inter-individual variability in running time to exhaustion in a large range of velocities (90% to 140% of $v\dot{V}O_2max$) is caused by the fact that running intensity was only expressed as a percentage of $v\dot{V}O_2max$. Indeed $v\dot{V}O_2max$ represents a selected aspect of the metabolic profile of the subjects. Therefore expressing intensity as

Table 1 Physiological measurements (mean ± SD) for the different field tests

Variables	units	$v\dot{V}O_2max$	tlim90	tlim100	tlim120	tlim140
$\dot{V}O_2$	($ml \times kg^{-1} \times min^{-1}$)	59.6 ± 5.5	57.4 ± 6.3	61.8 ± 6.2	61.0 ± 5.6	56.5 ± 4.5
[La]	($mmol \times l^{-1}$)	14.1 ± 3.9	13.6 ± 3.7	15.1 ± 2.7	15.7 ± 2.5	15.1 ± 2.7
HR	(bpm)	199 ± 8	192 ± 7	196 ± 6	190 ± 8*	185 ± 12*

*: significantly different from $v\dot{V}O_2max$

Table 2 Performance in the field tests

Subjects	v_{max} (km × h^{-1})	$v\dot{V}O_2max$ (km × h^{-1})	Cv (km × h^{-1})	tlim90 (s)	tlim100 (s)	tlim120 (s)	tlim140 (s)
1	31.4	16.0	13.7	950	450	154	65
2	30.3	16.0	13.9	1200	405	118	65
3	34.0	17.0	14.3	800	387	138	89
4	31.7	19.0	16.6	758	208	75	34
5	34.4	17.0	14.3	805	337	142	81
6	31.4	18.0	15.3	483	200	83	40
7	31.4	17.0	14.6	941	339	132	60
8	32.0	16.5	14.4	1126	524	109	70
9	28.6	15.0	12.1	480	258	120	73
10	32.1	17.0	14.5	847	465	150	72
Mean	31.7	16.9	14.4	839	357	122	65
SD	1.7	1.1	1.1	236	110	27	17

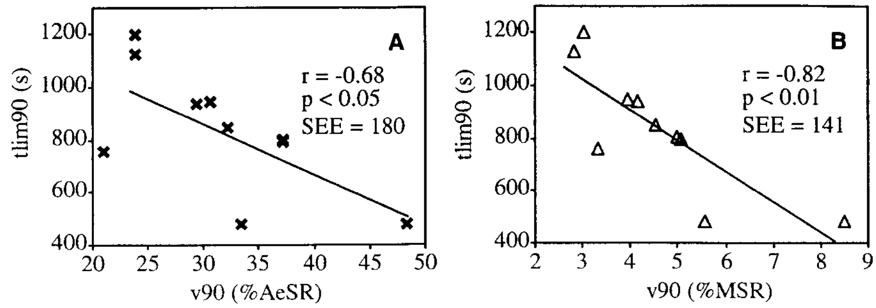

Fig. 2 Relationships between tlim90 and velocity (v90) expressed as **A**) percentages of aerobic speed reserve (%AeSR), and **B**) percentages of maximal speed reserve (%MSR).

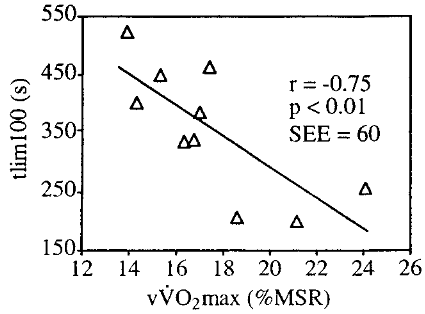

Fig. 3 Relationships between tlim100 and $v\dot{V}O_2max$ expressed as percentages of maximal speed reserve (%MSR).

a percentage of MSR for sub-maximal and maximal velocities and as a percentage of AnSR for supra-maximal velocities also allows individual differences in anaerobic work capacity to be taken into account and running times to exhaustion to be predicted accurately.

Sub-maximal velocity

The mean tlim90 was slightly lower than the values reported by Billat et al. [5] for high level runners (839 ± 236 s vs. 1015 ± 266 s). This difference in performance could be due to the difference in training level of the subjects. Indeed high-level runners are able to run longer than moderately-trained subjects at selected sub-maximal velocity. Nevertheless the coefficients of variations reported in both studies were similar: 28% in the present study and 26% for Billat et al. [5], indicating a great variability in tlim90 when velocity was only expressed as percentages of $v\dot{V}O_2max$.

We found that tlim90 was inversely related to velocity when expressed as a percentage of AeSR, but, as expected, a higher correlation was found between tlim90 and the velocity expressed as a percentage of MSR. This result is in accordance with the model of Ettema [9] and the experimental results of Billat et al. [6]. The greater 'v − Cv' is (i.e. the smaller v90 is when expressed as percentage of AeSR), the smaller the tlim will be. Moreover our results showed that v_{max} had to be taken into account to predict time to exhaustion. According to Equation 2, derived from Morton's 3-parameter model [18], time to exhaustion is dependent on anaerobic capacity and critical velocity but also on maximal velocity. This is in accordance with our results. From a practical point of view two subjects with equivalent Cv and $v\dot{V}O_2max$ but different v_{max} will have differences in time to exhaustion at the same velocity expressed as a percentage of $v\dot{V}O_2max$. Our results indicated that tlim could be accurately predicted and variability diminished if the intensity of exercise was expressed as the same percentage of the difference between v_{max} and Cv for sub-maximal runs.

No correlation was found between tlim90 and any of the measured physiological variables. Indeed this velocity (%$\dot{V}O_2max$) did not represent the same anaerobic contribution to energy supply. Thus tlim could not be correlated with anaerobic capacity or maximal lactate accumulation. On the other hand, if

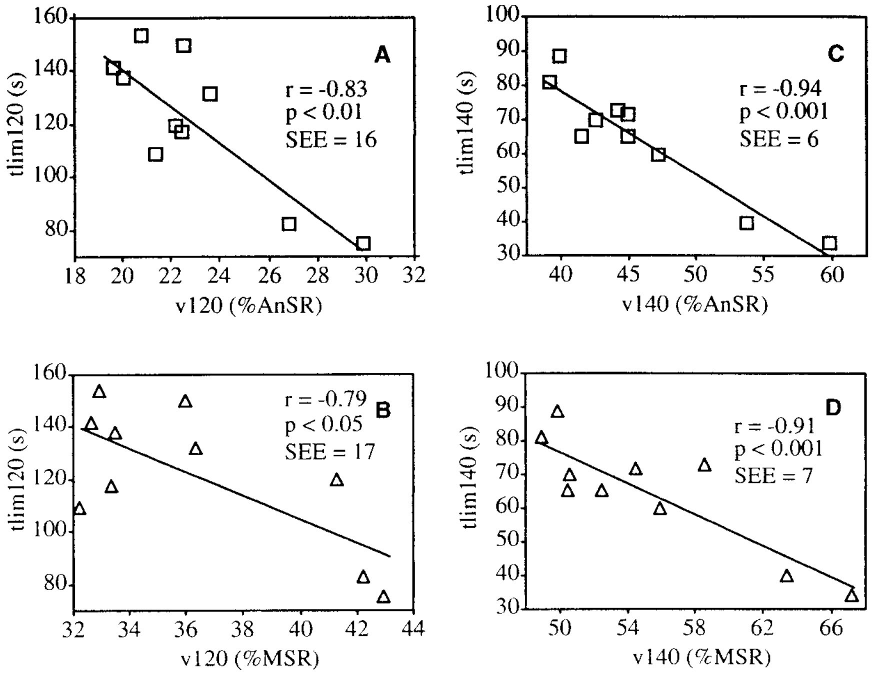

Fig. 4 Relationships between supramaximal tlim (tlim120 and tlim140) and velocity (v120 and v140) when expressed as **A**) and **C**) percentages of anaerobic speed reserve (%AnSR), and **B**) and **D**) percentages of maximal speed reserve (%MSR).

Table 3 Correlations between tlim (90, 100, 120, and 140) and $\dot{V}O_2max$, Cv (%$v\dot{V}O_2max$), [La] reached in tlim tests, anaerobic distance capacity, accumulated oxygen deficit

	$\dot{V}O_2max$ (ml × min^{-1} × kg^{-1})	Cv (%$v\dot{V}O_2max$)	$[La]_{max}$ (mmol × l^{-1})	ADC (m)	AOD (ml × kg^{-1})
tlim90 (s)	NS	r = 0.69 $p < 0.05$	NS	NS	NS
tlim100 (s)	NS	NS	r = 0.66 $p < 0.05$	r = 0.66 $p < 0.05$	r = 0.68 $p < 0.05$
tlim120 (s)	NS	NS	NS	r = 0.94 $p < 0.01$	NS
tlim140 (s)	NS	NS	NS	r = 0.91 $p < 0.01$	r = 0.66 $p < 0.05$

NS: non significant

velocity was set as a percentage of MSR, tlim could be expected to be related to physiological variables.

Maximal velocity

The mean tlim100 of our subjects was 357 ± 100 s. It was close to the values reported by Billat et al. [6] (360 ± 107 s), Padilla et al. [19] (420 ± 122 s), or Kachouri et al. [11] (482 ± 213 s). The coefficient of variation (31%) was in the same region, as those observed in the literature for tlim100, ranging from 25% to more than 50% [3]. Contrarily to Billat et al. [6] we failed to find any correlation between $v\dot{V}O_2max$ and tlim100. Difference between the subjects (well-trained *versus* moderately-trained) and a higher homogeneity may explain this controversial result.

As expected, we found a significant negative correlation between tlim100 and the velocity expressed as a percentage of MSR. Indeed, if $v\dot{V}O_2max$ represents the same aerobic intensity, anaerobic contribution to energy supply is different because Cv and v_{max} do not represent the same percentage of $v\dot{V}O_2max$ for all subjects. Hence tlim100 variability is large and not related to $v\dot{V}O_2max$. This result is in accordance with the results found for tlim90.

Moreover we found positive correlations between tlim100 and the post exercise [La] and accumulated oxygen deficit. These results are also in accordance with the Morton 3-parameter model. Indeed tlim is dependent on ADC. We failed to find these correlations with tlim90 because of the small gap between v90 and Cv. In this case a small error in Cv determination leads to a great overestimation or underestimation of tlim90.

Supra-maximal velocities

The coefficient of variation for tlim120 (22%) was close to the values reported by Barnett et al. [11] for cycling events (33%). Tlim120 and tlim140 were best related to velocities expressed as a percentage of AnSR. These results are in accordance with those of other authors [1,7]. Indeed Camus et al. [7] found that for supra-maximal events variability in running time to exhaustion was significantly reduced when exercise intensity was expressed with regard to the difference between the energy required to run at a selected supra-maximal velocity minus the maximal aerobic energy expenditure. In another study, for cycling events Barnett et al. [1] examined the validity of calculating supra-maximal power outputs using sub-maximal and maximal data in combination with data derived from a 30 s all-out sprint. They concluded that when the calculation of exercise intensity incorporated the measurement of both anaerobic and aerobic powers, the variance in tlim for supra-maximal exercises was reduced.

This conclusion for cycling exercise was the same as ours for running events. For supra-maximal velocities Cv is not a major decisive factor of tlim. Even if the anaerobic pathway participates to the energy supply at intensities lower than $\dot{V}O_2$max, the use of anaerobic capacity increases strongly for supra-maximal intensities. This is in accordance with our hypothesis that to estimate tlim, the running intensity had to be expressed in a unit representing the anaerobic contribution to energy supply but was also dependent on the anaerobic capacity estimated by ADC or AOD.

Conclusions

This study shows a close relationship between tlim and the velocity expressed as %MSR or %AnSR. It explains a part of the inter-individual variability in the time to exhaustion and allows accurate prediction of running times to exhaustion from Cv to v_{max}, which are dependent on the location of the running velocity between Cv (or $v\dot{V}O_2$max) and v_{max}. When running velocity is under or close to $v\dot{V}O_2$max, tlim is related to the relative intensity between Cv and v_{max}. For a similar relative intensity (%$v\dot{V}O_2$max) the position of each subject between Cv and v_{max} could considerably vary. These results show that to set running intensities, Cv and v_{max} should be taken into account instead of only using percentages of $v\dot{V}O_2$max. Variances in times to exhaustion might probably be reduced if the intensities were expressed as a percentage of v_{max} minus Cv. The relative expression of velocity, between Cv and v_{max}, integrated the whole energetic profile of the runners by taking into account both aerobic and anaerobic contributions. When the intensity is above $v\dot{V}O_2$max, it is better to predict tlim by expressing the velocity as a percentage of AnSR. Hence when the intensity drew nearer to v_{max}, tlim depended strongly on the intensity of running, relative to v_{max}. From a practical point of view expressing running velocity as %MSR or %AnSR could result in a diminished inter-individual variance in tlim. This is of particular interest for coaches in order to individualize their training intensities related to the same duration of running.

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