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Research article

Longitudinal study in 3,000 m male runners: relationship between performance and selected physiological parameters

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Abstract

The purpose of the present study was to analyze longitudinal changes in 3,000 m running performance and the relationship with selected physiological parameters. Eighteen well-trained male middle-distance runners were measured six times (x3 per year) throughout two consecutive competitive seasons. The following parameters were measured on each occasion: maximal oxygen uptake (VO_2max), running economy (RE), velocity at maximal oxygen uptake (vVO_2max), velocity at 4mmol L^{-1} blood lactate concentration (V4), and performance velocity ($km \cdot h^{-1}$) in 3,000 m time trials. Values ranged from 19.59 to 20.16 $km \cdot h^{-1}$, running performance; 197 to 207 $mL \cdot kg^{-1} \cdot km^{-1}$. RE; 17.2 to 17.7 $km \cdot h^{-1}$, V4; 67.1 to 72.5 $mL \cdot kg^{-1} \cdot min^{-1}$, VO_2max; and 19.8 to 20.2 $km \cdot h^{-1}$, vVO_2max. A hierarchical linear model was used to quantify longitudinal relationships between running performance and selected physiological variables. Running performance decreased significantly over time, between each time point the decrease in running velocity was 0.06 $km \cdot h^{-1}$. The variables that significantly explained performance changes were V4 and vVO_2max. Also, vVO_2max and V4 were the measures most strongly correlated with performance and can be used to predict 3,000 m race velocity. The best prediction formula for 3,000 m running performance was: $y = 0.646 + 0.626x + 0.416z$ (R^2=0.85); where y = V3,000 m velocity ($km \cdot h^{-1}$), x = V4 ($km \cdot h^{-1}$) and z = vVO_2max ($km \cdot h^{-1}$). The high predictive power of vVO_2max and V4 suggest that both coaches and athletes should give attention to improving these two physiological variables, in order to improve running performance.

Key words: Tracking; running performance; maximal oxygen uptake; blood lactate; running economy.

Introduction

Performance in middle distance running depends on several physiological parameters, mainly the ones which are related to maximal aerobic power (VO_2max). Parameters such as the maximal oxygen uptake, running economy (RE), velocity at 4 $mmol \cdot L^{-1}$ blood lactate concentration (V4), and the minimal velocity at which VO_2max occurs (vVO_2max), are often reported as having significant relationships with running performance (Billat, 1996; Houmard et al., 1991; Jones, 1998; Tanaka et al., 1986).

However, few studies (Brisswalter and Legros, 1994; Daniels, 1974; Houmard et al., 1991) have investigated longitudinal data concerning running performance and its relation with physiological variables. These earlier studies included only a few time points for evaluation and measured very few physiological parameters. In fact, some of them are either case studies or used a small sample size and applied somewhat unrealistic increments in training volume and intensity. For this reason there is a need for longer research periods, the use of more data points and the necessity to carry out the research in the athlete's natural training conditions. Using this approach it should be possible to determine changes in physiological, metabolic and performance measures in well-trained distance runners.

The maximal aerobic power is a key physiological marker of middle distance running performance and is also considered a good performance predictor in heterogeneous, but not in homogeneous groups (Noakes, 1988). Some studies have reported an improvement in VO_2max after training (Murase et al., 1981; Tanaka et al., 1984; 1986), while others have observed a stabilization throughout a certain training period (Houmard et al., 1991; Jones, 1998; Morgan et al., 1989). It has also been suggested that 'good' (lower) RE values could provide an important advantage during competition, despite low relationships reported between RE and middle distance running performance in heterogeneous groups (Cunningham, 1990; Grant et al., 1997; Svedenhag and Sjödin, 1984; Yoshida et al., 1993). Additionally, vVO_2max, a parameter which incorporates VO_2max and RE, has been closely related to middle distance running performance (Billat et al., 1994a; 1996; Jones, 1998). Another important physiological variable often associated with running performance is the maximal lactate steady state (Billat, 1996; Faude et al., 2009), which can be estimated using V4 (Foxdal et al., 1994). In fact, several longitudinal studies reported parallel improvements in both middle distance running performance and V4 (Acevedo and Goldfarb, 1989; Tanaka et al., 1984).

Thus, the main purpose of the study was to quantify the longitudinal changes (within-subject changes) and the relationship between 3,000 m running performance and selected physiological parameters in a group of middle distance runners over two seasons. Secondarily, we tried to determine which physiological variables can be used to predict 3,000 m running performance.

Methods

Participants

Eighteen well trained male middle-distance runners were evaluated (age: 20 ± 3 years; body mass: 64.1 ± 6.2 kg;

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height: 1.75 ± 0.05 m; 3,000 m performance: 9.05 ± 0.22 min; weekly training distance: 80.5 ± 31.5 km; training history: 6.0 ± 3.7 years). All subjects volunteered to participate and gave their written consent. All procedures were in accordance to the Declaration of Helsinki in respect to human research. The Institutional Review Board of the Polytechnic Institute of Bragança approved the study.

Procedures

The study was conducted over two consecutive years. Each runner was measured six times, three times per year, namely in November, two months after the beginning of the training season; in mid-season (March); and July, at the end of the season. In each assessement period, VO_2max, vVO_2max, RE, V4 and 3,000 m running performance were measured. For every given assessment period, data was collected within a seven day period. Training intensity was reduced during each testing period. All measurements were performed in three separate sessions: (i) running performance (3,000 m time trial) (ii) V4 determination and; (iii) VO_2max, RE and vVO_2max. The order of testing sessions was randomized between subjects and dates. There was at least a two-day recovery period between evaluation sessions.

To determine 3,000 m running performance we organized two groups, according to the participants' residence and others runners were invited. The race competition took place on a track and field stadium and the race was supervised by an official athletics judge. We chose a day without rain and with light winds. The instructions given to the runners were to run at the highest possible pace for the whole distance. This was not an official event but an organised time trial. We measured the individual performance times during the competition, and calculated the average running velocity.

Data collection

Oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$) was measured using a stationary breath-by-breath metabolic unit (Cortex, Model MetaLyzer 3B, Leipzig, Germany) which included a heart rate transmitter (Polar Electro Oy, Kempele, Finland). In a ventilated room, the metabolic unit was calibrated with 15 % oxygen concentration at the prevailing atmospheric pressure. Room temperature was automatically determined by the device. A 20.93% oxygen concentration and 0.03% carbon dioxide for ambient air were assumed. The apparatus had a 0.1% of error for O_2 and CO_2 determination. During each step, VO_2 values were averaged over the last 30 seconds, and this value was used in subsequent calculations.

To determine RE, four steps, each of 5 minutes duration, during sub-maximal (0% slope) treadmill running (Woodway, model 55 Sport, Germany) were used. The speed was constant during each step, and increased 1.45 $km \cdot h^{-1}$ from one step to the next. The rest period between steps was 4 minutes. The choice of workloads was individually prescribed, in a way that the speed used in the last step was close to, but lower than the athlete's V4 running velocity. During this protocol VO_2 was measured continuously. Then we calculated the regression line relating running velocity with oxygen uptake. The VO_2 corresponding to the velocity at 90% V4 was calculated from the regression equation.

Finally, RE, was determined at 90% V4, according to the following equation:

$$RE = 1000.\ VO_2\ /\ v \qquad \text{(equation 1)}$$

Where RE is running economy ($mL \cdot kg^{-1} \cdot km^{-1}$), VO_2 is oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$) and v is running velocity ($m \cdot min^{-1}$).

The assessment of VO_2 and vVO_2max was carried out ten minutes after the RE protocol. Each subject performed a continuous incremental test until voluntary exhaustion. The initial velocity was always lower than the athlete's V4 velocity. Increments of 1 $km \cdot h^{-1}$ every two minutes was used. The test was stopped when the subject signaled he was unable to continue running at the required velocity. Oxygen uptake, respiratory exchange ratio (RER) and heart rate (HR) were continuously recorded and averaged for the last 30 seconds of each two minute period (step).

The highest VO_2 and HR recorded in any of the last steps were accepted as maximum values (VO_2max and HRmax). The main criterion for VO_2max determination was the existence of a "plateau", meaning an increment equal to or lower than 2.0 $mL \cdot kg^{-1} \cdot min^{-1}$ in the last step or steps.

The VO_2max determination was made by analyzing the VO_2max measurement data. vVO_2max was taken as the velocity corresponding to the step at which the increment in VO_2 to the next step was lower than 2 $mL \cdot kg^{-1} \cdot min^{-1}$. When this was not observed, vVO_2max was taken as the velocity corresponding to VO_2max (Shephard, 2000). If the athlete could only do one half of the last two minute step we counted only half of the velocity increment.

The determination of running velocity at 4 $mmol \cdot L^{-1}$ blood lactate concentration (V4) was conducted during treadmill running (0 % slope) according to procedures previously described by Heck *et al*. (1985). Each test was preceded by an 8 to 10 minute warm up at a velocity lower than the first running velocity. Possible running velocities were: 12.2, 13.7, 15.1, 16.6, 18, 19.4 and 20.9 $km \cdot h^{-1}$. Four of these speeds were chosen for each runner according to his competitive level, and each speed was performed for 6 minutes. Between steps subjects had a passive rest period of 30 to 40 seconds to collect blood samples for lactate analysis (YSI, 1500L Sport analyzer, Yellow Springs, USA). The V4 values were calculated by linear interpolation, taking into account the values immediately above and below 4 $mmol \cdot L^{-1}$, obtained during the V4 testing protocol.

The estimated maximal endurance running speed (Vend) was assessed using VO_2max, RE and the estimated fraction of VO_2max sustained throughout the race (F), according to equation 2 (di Prampero et al., 1986), an accepted method to predict running performance velocity over different distances.

$$Vend = F.\ VO_2max.\ RE^{-1} \qquad \text{(equation 2)}$$

(VO_2max: $mL \cdot kg^{-1} \cdot min^{-1}$, RE: $mL \cdot kg^{-1} \cdot km^{-1}$, Vend: $km \cdot min^{-1}$)

We noted that the fraction of VO_2max (F) used in the 3,000 m competition could be expressed by the ratio between V3,000 m speed/vVO_2max and was very near

Table 1. Descriptive statistics, mean (±SD) throughout the two seasons for all variables assessed.

	1st Season (November)	1st Season (March)	1st Season (July)	2st Season (November)	2st Season (March)	2st Season (July)
Running performance ($km \cdot h^{-1}$)	19.94 (1.49)	20.16 (1.44)	19.86 (1.51)	19.59 (1.23)	19.82 1.47)	19.81 (1.43)
RE ($mL \cdot kg^{-1} \cdot km^{-1}$)	207 (18)	197 (12)	205 (10)	205 (13)	203 (15)	199 (12)
V4 ($km \cdot h^{-1}$)	17.7 (1.4)	17.5 (1.6)	17.2 (1.7)	17.6 (1.6)	17.6 (1.5)	17.4 (1.6)
VO_2max ($mL \cdot kg^{-1} \cdot min^{-1}$)	70.4 (9.0)	68.0 (6.2)	68.9 (6.2)	72.5 (7.2)	67.8 (7.1)	67.1 (7.5)
vVO_2max ($km \cdot h^{-1}$)	19.8 (1.4)	19.8 (1.4)	19.9 (1.5)	20.2 (1.4)	19.8 (1.4)	20.0 (1.6)

to unity, therefore we assumed F = 1.

Statistical analysis

Descriptive statistics (means and standard deviations) were computed for all variables. A hierarchical linear model (HLM) was used to analyze the relationship between 3,000 m running performance and selected physiological variables over the 6 evaluations during the two seasons. Maximum likelihood estimation was used with the HML5 statistical software (Raudenbush et al. 2001).

'Tracking' - the number of times that each individual remained in the same 'track' of performance (e.g. quartile), determined from individual performance times, was calculated using Cohen´s kappa statistic with Longitudinal Data Analysis software version 3.0 (Schneiderman et al., 1993). Qualitative criteria of Kappa [moderate (0.41–0.60), good (0.61–0.80) and very good (0.81–1.00)] were used (Landis and Koch, 1977). Simple and multiple regressions between different variables were calculated. The level of statistical significance was set at $p \leq 0.05$.

Results

Descriptive statistics (mean ± SD) for performance and physiological variables assessed on each occasion over the two seasons are shown in Table 1.

The hierachical linear model showed a significant decrease in running performance over time. The estimated decrease in running performce, between each measurement occasion was 0.06 $km \cdot h^{-1}$. The effect of RE and VO_2max were not significant and they were not included in the final model. The physiological variables that best explained changes in running performance were V4 and vVO_2max. For each $km \cdot h^{-1}$ change in V4 or vVO_2max the change in running performance was 0.43 and 0.32 $km \cdot h^{-1}$ respectivly (Table 2).

With regard to the qualitative criterion of tracking indices (Cohen´s Kappa), analysis showed '*moderate' as a* descriptor for both RE (k=0.54) and VO_2max (k=0.55); in contrast '*good'* described both V4 (k=0.70) and v VO_2 max (k=0.71).

Discussion

Interestingly, the longitudinal changes in running performance, analysed by HLM, showed that 3,000 m running performance decreased significantly over time. The decrease was -0.06 $km \cdot h^{-1}$. However, V4 and vVO_2max had a positive contribution to the performance modification, namely 0.43 $km \cdot h^{-1}$ and 0.32 $km \cdot h^{-1}$ respectively (Table 2). This means that an athlete posessing high values in these two physiological variables could have diminished decrements in performance over time or even shown improved performance.

The performance decreases could be due to different factors: (i) the average training volume, although relatively high, did not increase significantly during the 2 year period; (ii) the training aims were not specifically challenging enough to improve 3,000 m performance, because they were also involved in other race distances; (iii) the training process was not unified, the athletes followed differing training programmes under the guidance of different coaches.

The trend towards a decrease in running performance has not been previously reported (Jones, 1998; Tanaka et al., 1984; 1986). Tanaka et al. (1984) found significant improvements in 5,000 m and 10,000 m running performance (13.2 sec and 1 min 8 sec respectively) in university runners during a 9 months period. In another study, the same group also reported significant improvements in 10 km performance after a four month training period. In comparison, other studies found no improvement in 8 km performance, also using university runners (Houmard et al., 1991). These findings suggest that improvement in running performance could be associated with a period of training in which the workload was higher than usual. However, substantial increments in training loads are difficult to apply simultaneously in a group of runners with different coaches over a long time period. In the present study, training volume and intensity were not intentionally

Table 2. Parameters specification for the final Hierarchical Linear Model with standard errors (SE) and confidence intervals. Running performance (V3000 m speed, in $km \cdot h^{-1}$) is the dependent variable. V4 and vVO_2max are in $km \cdot h^{-1}$.

Parameter	Estimate(SE)	95% Confidence Interval
Fixed effect		
Intercept	19.86 (.13)	19.61 — 20.11
Time	-.06 (.02)	-.10 — -.02
V4	.43 (.09)	.25 — .61
vVO_2max	.32 (.10)	.12 — .52
Random effects	**Variance**	
BMI (Baseline)	.54 *	
Level 1 error	.45	

* significant at p < 0.001

increased, because athletes followed their usual training schedules, as implemented by their coaches.

Traditionally VO_2max and RE are considered important variables to explain running performance. In the present study VO_2max and RE were not included as explanatory variables in modelling 3,000 m running performance (using HLM). This meant that RE and VO_2max were not important variables to explain changes in running performance. Indeed the weak association between RE and performance had already been observed in cross-sectional studies (Billat et al., 1994a; 1994c; 1996). Regarding all physiological variables, RE seemed to be the least important predictor of 3,000 m performance. In fact, either higher or lower RE can be found in 3,000 m athletes of any competitive level. This could be partially explained by the comparatively short race duration, and it is likely that the role of RE becomes more important as race distance increases.

The results of the present study demonstrate that V4 and vVO_2max were the variables that can best explain changes in 3,000 m running performance over time. These variables have also been identified in earlier studies involving middle distance runners (Colaço, 2002; Novo and Santos, 2002; Santos and Kruger, 2002). V4, as an expression of maximal lactate steady state (Heck et al., 1985), is one of the most important variables in distance running and it assumes great relevance in 3,000 m running performance.

3,000 m running velocity ranged between 97 and 101% vVO_2max (mean 100%). Which suggests that 3,000 m race pace utilises approximately 100% of the VO_2max, as previously observed by e.g. Billat et al. (1994b) and Jones (1998). One possible explanation for the great importance of vVO_2max is that this variable integrates both VO_2max and RE in the same measure. Therefore, the relationship between vVO_2max and 3,000 m performance makes this physiological variable one of the most relevant for runners and coaches. We consider that determination of vVO_2max provides an important tool which can be used in training, e.g. as a speed suitable for use during interval training.

Our results show that the training stimulus, specifically in terms of intensity and duration, was not strong enough to promote substantial improvements in 3,000 m performance. Although we did not gather an extensive amount of data related to the training process throughout the two year period, we had enough data from coaches to conclude that the average weekly training volume did not increase significantly throughout the six assessment points. This suggests that a higher intensity or greater training volume, and/or other modifications to the training process (e.g. more efficient periodization designs, greater intensity, use of plyometrics, more efficient recovery routines) may be needed in order to significantly improve athletes' running performance. As a result, we were unable to confirm our initial hypothesis concerning the improvement in running performance.

We intended to determine which physiological variable could be considered the best predictor of 3,000 m performance and compare it with the procedure proposed by di Prampero and coworkers (1986) (equation 2). In the present study, the comparison between 3,000 m running performance (V3,000 m speed), vVO_2max and Vend showed a great similarity: the ratio between actual V3,000 m speed and estimated speed calculated from the equation of di Prampero et al. (1986) (Vend), ranged between 0.96 and 0.99. We also noted that the fraction of VO_2max (F) used in the 3,000 m time trials and expressed by the ratio between V3,000 m speed / vVO_2max was nearly 1. This meant that, in running competitions, and when using distances above 3,000 m, the value of F will progressively decrease as distance increases. On the other hand, in running competitions under 3,000 m, and since F cannot exceed 1, the contribution of anaerobic metabolism becomes progressively more important. In this context, and since the di Prampero equation does not consider the contribution of anaerobic metabolism, it seems that the di Prampero equation may not be the most appropriate in order to estimate running performance under 3,000 m.

In the present study we tried to predict 3,000 m running performance based on selected physiological parameters. Results of both linear and multiple regression analysis showed that either V4 or vVO_2max can be used to individually predict running performance (R^2 = 0.80 and 0.77 respectively). However, 3,000 m running performance was best predicted using both V4 and vVO_2max in the same equation. Thus:

$$y = 0.646 + 0.626x + 0.416z;\ R^2 = 0.85 \qquad \text{(equation 3)}$$

where y is the V3,000 m speed ($km \cdot h^{-1}$), x is V4 ($km \cdot h^{-1}$) and z is vVO_2max ($km \cdot h^{-1}$).

The high predictive power of vVO_2max and V4 suggest that both coaches and athletes should give attention to improving these two physiological variables, in order to improve 3,000 m running performance.

Conclusion

The longitudinal changes in running performance, analysed by HLM, showed that 3,000 m running performance decreased significantly over time. Among physiological measures, V4 and vVO_2max were the parameters most related to changes in performance. In addition, these variables can be used to predict middle distance running performance, particularly if they are used simultaneously (R^2 = 0.85). The high predictive power of vVO_2max and V4 suggest that both coaches and athletes should give attention to improving these two physiological variables, in order to improve 3,000 m running performance.

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Key points

- V4 and vVO_2max are the most important physiological variables to explain longitudinal changes in 3000 m running performance;
- 3000 m running performance prediction is better if one uses both V4 and vVO_2max in the same formula: $y = 0.646 + 0.626x + 0.416z$; R2=0.85, where y is the Vrace (km/h), x is V4 (km/h) and z is vVO_2max (km/h).
- The V4 and vVO_2max can be used for training control purposes.

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