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Multidimensional analysis of metabolism contributions involved in running track tests

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Summary
Introduction: It is difficult to interpret the training induced changes in middle-distance running, since numerous aerobic and anaerobic determinants of the performance are interdependent. Several aerobic and anaerobic tests are available but their results, particularly those from anaerobic tests, may be discordant, not providing univocal interpretation of training. The purpose of this study is to use a multidimensional approach to distinguish aerobic and anaerobic capacities assessed by two running tests on a track: the maximal anaerobic running test (MART) and V_{O_2MAX} tests.
Method: Eleven runners carried out two maximal tests on a synthetic track before and after a 4-week training period: (i) a maximal test to determine V_{O_2MAX}, the velocity associated with V_{O_2MAX} (vV_{O_2MAX}) and the velocity at the lactate threshold (v_{LT}), (ii) a maximal anaerobic running test to estimate anaerobic capacity. An all-out test run at v_{LT} + 50% of the difference between v_{LT} and vV_{O_2MAX}, known to be affected by both aerobic and anaerobic energy production, was used to test this approach.
Results: A principal components analysis (PCA) shows that two components (i.e., aerobic and anaerobic) explained 79% of the variation in the physiological variables. The PCA suggests that V_{O_2MAX} and MART tests assess the aerobic and the anaerobic capacities, respectively. In contrast, the performance in the all-out test is affected by both aerobic and anaerobic energy production. The PCA shows that v_{LT} and ΔP (difference between the maximal power of the MART and V_{O_2MAX}) are clear markers of the long-term endurance and the anaerobic capacity, respectively.
Conclusion: This multidimensional approach can be a useful way to disentangle the aerobic and anaerobic components of track tests.

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Introduction

The effect of training on the physiological factors determining performance in middle- and long-distance running remains a topic of great interest among coaches and scientists, and raises many questions. Indeed, success in middle-distance running (800—1500 m) depends on the athlete's ability to maintain a velocity which corresponds to around 110—120% of the velocity of maximal oxygen consumption (vV_{O_2MAX}).[4] According to Spencer and Gastin,[25] the total relative contribution of the aerobic energy system for the 800- and 1500-m running events are 66 and 84%, respectively. In consequence, considering the numerous physiological variables involved in the performance (i.e., aerobic and anaerobic characteristics) and the fact that some of them are interdependent, it is difficult to interpret the training induced changes, especially when the sample size is small. The small number of well-trained athletes in experimental training studies is therefore a major problem for providing information about the effectiveness of training programs. Several aerobic and anaerobic tests and parameters are available for coaches and scientists to prescribe and to monitor training programmes, but the results of the tests, particularly anaerobic tests, are sometimes discordant, and do not provide univocal interpretation of training; therefore, they can be difficult to be used by coaches and scientists.

The anaerobic capacity has proved to be a difficult metabolic construct to measure and current anaerobic tests have significant limitations. The accumulated oxygen deficit method, which has been proposed to quantify anaerobic energy production, consists of several time-consuming measures and therefore is not a practical method for elite athletes.[17] A maximal anaerobic running test (MART) has been established by Rusko et al. (1993) to assess the anaerobic performance characteristics. It has been reported to be a practical method and to provide relevant information about the effectiveness of interval training programs.[22] For the test results to have optimum practical significance, the exercise mode must be specific to the sport. For running, it is desirable to assess the runners on a track in a simulated competitive condition. Recently, the MART protocol has been applied on a track.[21] Thus, the first purpose of this study is to investigate the applicability of the MART protocol to track running.

Psychological studies commonly use multivariate statistical analysis to reduce the number of variables to a lower number of independent components.[27] This statistical approach has recently been used to identify performance determinants,[8,13,18] but to our knowledge no such studies have focused on testing procedures for middle-distance running. The second purpose of our study is then to apply a multidimensional approach to discriminate between the relative contributions of aerobic and anaerobic metabolisms involved in testing procedures used on the track to assess aerobic and anaerobic capacities. Moreover, in order to test the sensitivity of this approach, we also use an ''all out running test to exhaustion'' (T_{max}) at a velocity corresponding to the midway between the lactate threshold and the velocity associated with the maximal oxygen consumption (the so-called $v\Delta 50$ velocity), known to maximally stress both the aerobic and anaerobic energy systems.[6] Thus, the purpose of this study is to use a multidimensional approach to distinguish aerobic and anaerobic capacities assessed by two running tests on a track: the MART and V_{O_2MAX} tests.

Material and methods

Subjects

Eleven regional-level middle-distance runners (four women and seven men) provided voluntary written informed consent in accordance with the guidelines of the Ethical Committee of the University of Paris. They had been training three to four times per week for at least 4 years. Their mean ± S.E. age, height, mass and V_{O_2MAX} were 31 ± 5.2 years, 171.27 ± 7.2 cm, 62.09 ± 9.2 kg, and 60.76 ± 4.14 ml min^{-1} kg^{-1}, respectively. This study was carried out at the beginning of the ''build-up'' phase of training, 3 months after the competitive season (November). All subjects were instructed to adhere to their normal diets throughout the testing procedures and were advised to refrain during from caffeine or alcohol preceding day prior to testing.

Experimental procedure

Subjects carried out three tests on a synthetic 400-m track (temperature of 16.2 ± 2.3 °C [mean ± S.E.] and barometric pressure of 752 ± 5 mmHg) before and after a 4-week training program currently used by trainers and athletes to improve the vV_{O_2MAX}. This training program consisted, per week, of two intense short- and long-interval training sessions performed at 92 and 100% vV_{O_2MAX}, respectively, and one recovery run session that was run for 30 min at 60% of the vV_{O_2MAX}.

The first test was an incremental test to determine V_{O_2MAX}, vV_{O_2MAX}, the running velocity at

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the lactate threshold (v_{LT}), the median velocity between v_{LT} and vV_{O_2MAX} ($v\Delta50$), and the energy cost of running (ECR). The second test was the maximal anaerobic running test (MART) to estimate the anaerobic performance capacity using the protocol described in Rusko and co-workers[21] The third test was a continuous running to exhaustion at a constant velocity ($v\Delta50$) to determine the time to exhaustion (T_{max}). Throughout the tests, the athletes adopted the required velocity as indicated by audio cues via Walkman. The rhythm cue specified the speed needed to cover 25 m. Visual marks were set at 25-m intervals along the track (inside the first line). The athletes were required to do only one test per day, at the same time of a day, and were required to rest during the day between the tests. The athletes were familiar with the field tests and before the experiment they were given the opportunity to become familiar with the equipment and testing protocols that would be used during the trial. Strong vocal encouragement was given throughout the tests.

Material

The variables characterizing respiratory and pulmonary gas exchange were measured by using a portable breath-by-breath gas analyser (Cosmed K4b^2, Rome, Italy), which was calibrated before each test according to the manufacturer's instructions.[11,16] Expired gases were averaged every 5 s (Data Management Software, Cosmed, Rome, Italy). Heart rate (HR) was monitored throughout the tests (Polar, Kempele, Finland). Fingertip capillary blood samples were collected in capillary tubes (10 μl) and were analysed for blood lactate concentration (L) using a Doctor Lange (GmbH, Berlin, Germany). Velocity during the MART was recorded using photoelectric cells (Brower Timing Systems, USA, UT, Salt Lake City). Subjects performed testing sessions on a 400-m synthetic athletic track.

Data collection procedures

V_{O_2MAX} test

The initial test velocity was set at 12 km h^{-1} for the women and 14 km h^{-1} for the men and increased by 1 km h^{-1} every 3 min until voluntary exhaustion. Fingertip capillary blood samples were collected before the test, between each stage (30-s rest), immediately after exhaustion, and after a 3-min recovery period. The V_{O_2MAX} was defined as the highest V_{O_2} value obtained in two successive 15-s intervals. The criteria used to determine V_{O_2MAX} were: (1) an increase in running speed without a concomitant increase in V_{O_2}; (2) a heart rate within 10% of age-predicted maximum; (3) a blood lactate above 8 mol l^{-1}; (4) a respiratory exchange ratio over 1.1. The vV_{O_2MAX} was defined as the lowest velocity at which the V_{O_2MAX} occurred.[3] If the vV_{O_2MAX} was maintained for half- rather than all-of the last stage, it was then considered as the median velocity maintained during the last two stages.[14] The v_{LT} was defined as the velocity for which an increase in lactate concentration corresponding to 1 mmol l^{-1} occurs between 3.5 and 5.0 mmol l^{-1}, expressed as km h^{-1} and as %vV_{O_2MAX}.[1] The $v\Delta50$ was the velocity for which the V_{O_2} slow component may lead the oxygen consumption to its maximum (V_{O_2MAX}).[5,9] The energy cost of running (ECR, ml m^{-1} kg^{-1}) was defined as the ratio between oxygen consumption (ml min^{-1} kg^{-1}) and running velocity (m min^{-1}) measured from a sub-lactate threshold running velocity.[10]

The maximal anaerobic running test (MART)

The MART was adapted for the track following the protocol of treadmill test established by Rusko et al. (1993) and using similar velocities as on the treadmill. Before the MART, subjects performed a 20-min standardised warm-up. The MART consisted of $n \times 150$-m runs with a 100-s passive recovery period between the runs. A 10-m acceleration phase was not included in the running distance. The timing started when athletes passed the 150-m starting line and was stopped when athletes ran through the finishing line. The velocity of the first run was 14.2 km h^{-1} (women) or 17.1 km h^{-1} (men). Thereafter, the velocity was increased by 1.4 km h^{-1} for each consecutive run until exhaustion. Each participant ran from seven to ten 150-m runs. Following Rusko et al.,[24] the fastest 150-m velocity was selected as the maximal velocity in the MART (v_{MART}; i.e., maximal anaerobic work capacity). Immediately after a 40-s passive recovery as well as 2.5 and 5.0 min after exhaustion, fingertip capillary blood samples were collected. No blood lactates were found above 5 mmol l^{-1} after the first run.[24] The maximal power (P_{max}) in the MART was expressed as the individual oxygen demand (ml kg^{-1} min^{-1}) of the fastest 150 m (i.e., v_{MART}) and was calculated by extrapolating the individual oxygen cost from submaximal velocity to v_{MART}. The difference between P_{max} and V_{O_2MAX} (ΔP, ml kg^{-1} min^{-1}) and the highest blood lactate concentration after the MART (L_{max},

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mmol l^{-1}) were used to estimate the anaerobic capacity.[24]

Exhaustive running test (T_{max})

After a standardised warm-up (15 min at 60% vV_{O_2MAX}), the runners had to maintain their pre-training velocity $v\Delta 50$ until they were exhausted, in order to determine the time to exhaustion (T_{max}). A fingertip capillary blood sample was collected after the warm-up, and at 1 and 3 min after the exercise to determine the maximal blood lactate concentration.

Statistical analysis

A principal components analysis (PCA) was used to bring the large number of physiological variables down to a smaller number of independent components. A PCA enables an estimate of redundancy in dependent variable by identifying common sources of variance.[26] Because of the large number of dependent variables relative to the low number of subjects, the PCA was applied to all variables measured from the pre- and post-tests. A varimax rotation solution (with orthogonal components) was adopted with the constraint that two components should be extracted. We considered that a component accounted significantly for a given variable if its corresponding loading exceeded 0.70, which means that 49% of the variance of the variable was explained by that particular component. Although this criterion might appear conservative, it is a commonly adopted criterion in order to generalize data obtained from a small number of subjects.[7] The communality (h^2) represents the proportion of the variance of a particular variable which is explained by the extracted components. The SPSS statistical package (Version 10; SPSS, Inc., Chicago, IL, USA) was used to perform the various analyses. Results are presented as means ± standard errors (S.E.). The level of significance was set to 0.05 and 0.001.

Results

Table 1 presents the aerobic and anaerobic performance and training characteristics of subjects determined from the field tests (pre- and post-training programs).

Table 2 shows the correlation matrix of relationships among the 12 variables. Variables such as V_{O_2MAX}, vV_{O_2MAX}, $v\Delta 50$, v_{LT}, and ECR were significantly correlated to each other, correlations ranging from 0.48 to 0.96 ($p < 0.05$, $p < 0.001$).

The PCA was performed on the 12 original physiological variables and resulted in the extraction of 2 main components which accounted for 79% of the total variance in the physiological variables. Table 3 shows loading of variables on components, communalities, and percentage of variance and cumulative variance. The dependent variables explained by the first component were: V_{O_2MAX}, vV_{O_2MAX}, $v\Delta 50$, v_{LT}, and ECR, related to the aerobic energy system. The second component explained the variables related to the anaerobic energy system, i.e., v_{MART}, %MART, P_{max} and ΔP. Notice that the ECR is negatively related to the first component unlike the other vari-

Table 1 Mean ± S.E. of aerobics and anaerobics variables before (pre) and following (post) training

Variables	Pre-training	Post-training	P
V_{O_2MAX} (ml O_2 kg^{-1} min^{-1})	59.2 ± 3.8	60.2 ± 4.5	NS
vV_{O_2MAX} (km h^{-1})	17.7 ± 1.5	18.1 ± 1.5	0.034
$v\Delta 50$ (km h^{-1})	16.2 ± 1.4	16.9 ± 1.3	0.05
v_{LT} (km h^{-1})	14.7 ± 1.3	15.7 ± 1.2	0.001
$\%V_{O_2MAX}$	84.6 ± 1.3	85.6 ± 1.2	0.001
ECR (ml O_2 km^{-1} h^{-1})	201.2 ± 5.5	197.5 ± 4.1	0.027
v_{MART} (km h^{-1})	25.1 ± 2.8	25.2 ± 2.6	NS
$\%v_{MART}$	141 ± 3.8	137.5 ± 3.7	NS
P_{max} (ml O_2 kg^{-1} min^{-1})	83.8 ± 8.1	81.9 ± 8.2	0.036
ΔP (ml O_2 kg^{-1} min^{-1})	24.8 ± 5.1	21.7 ± 4.5	0.001
L_{max} (mmol l^{-1})	13.3 ± 2.6	13.6 ± 2.6	NS
T_{max} (s)	507.6 ± 121.4	563.9 ± 151.8	NS

Significant correlations between variables; $P < 0.05$. V_{O_2MAX}, maximal oxygen uptake; vV_{O_2MAX}, velocity associated with the achievement of V_{O_2MAX}; v_{LT}, velocity associated with the lactate threshold; $\%vV_{O_2MAX}$, velocity associated with the lactate threshold expressed in $\%vV_{O_2MAX}$; ECR, running energy cost; $v\Delta 50$, the median velocity between v_{LT} and vV_{O_2MAX}; v_{MART}, the faster velocity in the MART; %MART, v_{MART} expressed in $\%vV_{O_2MAX}$; P_{max}, maximal running power; ΔP, difference between P_{max} and V_{O_2MAX}; L_{max}, peak blood lactate concentration in the MART; T_{max}, time to exhaustion at $v\Delta 50$.

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Table 2 Correlation matrix of relationships among the 12 variables

	T_{lim} test	V_{O_2MAX} test						MART test				
	T_{max}	V_{O_2MAX}	vV_{O_2MAX}	$v\Delta 50$	v_{LT}	$\%V_{O_2MAX}$	ERC	v_{MART}	% MART	P_{max}	ΔP	L_{max}
T_{lim} test												
T_{max}	1.000											
V_{O_2MAX} test												
V_{O_2MAX}	0.445*	1.000										
vV_{O_2MAX}	0.340	0.959*	1.000									
$v\Delta 50$	0.342	0.933*	0.884*	1.000								
v_{LT}	0.294	0.889*	0.935*	0.976*	1.000							
$\%V_{O_2}$ MAX	0.070	0.000	0.026	0.186	0.378	1.000						
ERC	0.093	−0.480*	0.688*	0.717*	0.717*	0.227	1.000					
MART test												
v_{MART}	0.474*	0.907*	0.891*	0.834*	0.749*	0.213	0.476*	1.000				
%MART	0.438*	0.369	0.272	0.175	0.073	0.500*	0.103	0.677*	1.000			
P_{max}	0.550*	0.867*	0.796*	0.725*	0.630*	0.299	0.260	0.972*	0.774*	1.000		
ΔP	0.147	0.279	0.317	0.341	0.365	0.192	0.413	0.281	0.076	0.194	1.000	
L_{max}	0.303	0.166	0.181	0.191	0.250	0.242	0.290	0.071	0.157	0.008	0.231	1.000

V_{O_2MAX}, maximal oxygen uptake; vV_{O_2MAX}, velocity associated with the achievement of V_{O_2MAX}; v_{LT}, velocity associated with the lactate threshold; $\%vV_{O_2MAX}$, velocity associated with the lactate threshold expressed in $\%vV_{O_2MAX}$; ECR, running energy cost; $v\Delta 50$, the median velocity between v_{LT} and vV_{O_2MAX}; v_{MART}, the faster velocity in the MART; %MART, v_{MART} expressed in $\%vV_{O_2MAX}$; P_{max}, maximal running power; ΔP, difference between P_{max} and V_{O_2MAX}; L_{max}, peak blood lactate concentration in the MART; T_{max}, time to exhaustion at $v\Delta 50$.

* Significant correlations between variables; $P < 0.05$.

Table 3 Results of PCA: component loading, communalities h^2, % of explained variance

Testing procedure	Variables	Component 1	Component 2	Communality h^2
Running limit-time test	T_{max}	0.144	0.604	0.386
V_{O_2MAX} test	V_{O_2MAX}	**0.807**[a]	0.517	0.919
	vV_{O_2MAX}	**0.895**[a]	0.403	0.962
	$v\Delta50$	**0.944**[a]	0.290	0.976
	v_{LT}	**0.974**[a]	0.152	0.971
	v_{LT} (%V_{O_2MAX})	0.409	−0.621	0.554
	ERC	**−0.820**[a]	0.134	0.691
MART test	v_{MART}	0.662	**0.743**[a]	0.990
	%MART	−0.047	**0.925**[a]	0.858
	P_{max}	0.507	**0.855**[a]	0.988
	ΔP	0.155	**0.965**[a]	0.956
	L_{max}	0.491	0.074	0.247
	Explained variance	42.6%	36.5%	

V_{O_2MAX}, maximal oxygen uptake; vV_{O_2MAX}, velocity associated with the achievement of V_{O_2MAX}; v_{LT}, velocity associated with the lactate threshold; ECR, running energy cost; $v\Delta50$, the median velocity between v_{LT} and vV_{O_2MAX}; v_{MART}, the faster velocity in the MART.

[a] Component loading > 0.70.

ables explained by that component. This is due to the fact that a high aerobic capacity is reflected on the one hand by low ECR values, and on the other hand by high values of vV_{O_2MAX}, $v\Delta50$, v_{LT} (i.e., a decrease of oxygen uptake at sub-maximal velocity). The results of the PCA show that v_{LT} and ΔP loaded highly on the ''aerobic component'' and the ''anaerobic component'', with loading of 0.97 and 0.97, respectively (Table 3). T_{max}, L_{max} and v_{LT} (%V_{O_2MAX}) showed low correlations with the components, with low communality, and as a result were not extracted in the PCA.

Discussion

The PCA was carried out to summarize the physiological factors of the performance in all-out running test in a smaller number of independent factors. Our multidimensional approach allowed us: (i) to validate that the V_{O_2MAX} and MART tests are two distinct testing procedures sensitive to aerobic and anaerobic capacities, respectively, and (ii) to confirm that both aerobic and anaerobic components affect T_{max}.

According to the results of the PCA, a two-component model was extracted: the first component groups variables related to the aerobic energy system (i.e., V_{O_2MAX}, vV_{O_2MAX}, $v\Delta50$, v_{LT}, ECR); the second component groups variables associated with the anaerobic energy system (i.e., v_{MART}, %MART, P_{max} and ΔP). As each component of the PCA model collected together highly interrelated variables associated to aerobic versus anaerobic energy systems, we could distinguish the maximal aerobic test (V_{O_2MAX} test) and the maximal anaerobic running test (MART). Thus, the PCA provided some evidence that the proposed multidimensional approach is able to discriminate between two testing procedures. Furthermore, it confirmed that the MART protocol applied on the track measures anaerobic performance characteristics, which are relevant for middle-distance runners, as established in previous studies.[15,20,23] The PCA is a mathematical technique which must be considered only as a starting point in multivariate analysis, i.e., as the extraction of an initial solution. Here, it allowed us to reduce the 12 original variables to just 2 factors, which can now be used for further analysis. It would have been interesting to compare the results of the PCA with a track running performance. However, because of the training period (i.e., the beginning of the ''build-up'' phase of training) the athletes did not agree to complete a track running trial at their preferred distance (risks of injuries, motivation). Thus, further studies are needed to show that the PCA could be a useful adjunct to a regression model for predicting middle-distance running performance and further training intervention studies. It would be interesting to test the effect of training on the dependent variables, which best described the aerobic and anaerobic components according to the PCA analysis, by using the analysis of variance.

The 2 extracted components (i.e., aerobic and anaerobic components) accounted for most of the variation (79%) in the 12 original physiological variables. The variance explained by the two

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components was large, compared to previous studies using a similar approach.[8,13,18] The fact that some variables (T_{max}, L_{max} and $\%V_{O_2MAX}$) had small loadings on a PCA factor means that they were not specific to the extracted factors. Indeed, the value of the component loading of T_{max} (0.6) means that 36% of its variance was explained by the component reflecting the anaerobic energy system. The correlation matrix (Table 1) shows that T_{max} was weakly but significantly correlated to V_{O_2MAX}, v_{MART} and $\%V_{O_2MAX}$, with correlation coefficients ranging from 0.44 to 0.47. These findings as well as the results of a previous study suggest that although the T_{max} at $v\Delta50$ (i.e., 91.3% vV_{O_2MAX}) has a large aerobic component, it may also reflect runners' ability to exercise anaerobically.[6,12] Indeed, it has been shown that the time to exhaustion at 90% of vV_{O_2MAX} depends on the ratio between the anaerobic running capacity and the difference between $v\Delta50$ and the critical speed (i.e., the maximal velocity which can be sustained over a long period of time without fatigue) that represents the aerobic speed reserve.[6] Although distance running requires high aerobic power, the runners who can keep their muscle recruitment at the highest level perform the best in distance running race.[23] This emphasizes the role of the neuromuscular system and the anaerobic performance characteristics in distance running performance. Thus, as a direct measurement of the mixed contribution of aerobic and anaerobic metabolisms, the T_{max} test could be used as a pre-requirement to evaluate specific adaptation of athletes on the track.

Moreover, the low factor loading of L_{max} suggests a low predictive value of this variable for distinguishing the effect of training on aerobic and anaerobic capacities. Although this variable was not explained univocally by the PCA, it does not mean that L_{max} is not important. As noted by Nummela and Rusko (1996) the validity of the peak blood lactate as an indicator of lactic capacity remains questionable and future research is needed to clarify the usefulness of this variable to assess anaerobic capacity. Thus, further investigations are needed to improve our understanding of the relationship between these variables and the middle-distance running performance. Nevertheless, the PCA helps us to understand the underlying structure of the original data and to reduce the sources of discordant information which could obscure the interpretation of the results of the testing procedures.

Another interesting result of this study is that v_{LT} and ΔP explain 94 and 93% of the total variance of the first (i.e., ''aerobic'') and the second (i.e., ''anaerobic'') component, respectively. These two variables might then be sufficient to describe the effects of training on the physiological factors determining middle-distance running performance. We noted that the extraction of two components reflects the energy production of runners over a large range of intensities, from v_{LT} (i.e., moderate intensity) to ΔP (i.e., supramaximal intensity). This could also explain why the $\%V_{O_2MAX}$ is not clearly explained by the extracted factors. Indeed, the component loading of $\%V_{O_2MAX}$ was shared between the extracted ''aerobic'' and ''anaerobic'' components with respective contributions of 0.409 and 0.601. So, the PCA revealed that v_{LT} is a clear marker of endurance capacity. The lactate threshold is the key factor to maintain a relatively high velocity over middle-distance running events or to sustain a high fraction of V_{O_2MAX} over a long-distance running as shown in previous studies.[4]

It should be noted that V_{O_2MAX} showed a relatively high loading on the first component (0.807; i.e., 65% of the total variance) but also a significant loading on the second component (0.517; i.e., 27% of the total variance). It has been argued that the performance of an athlete in a maximal aerobic test depends on the capacity to support lactic acidosis involved in the V_{O_2MAX} test.[2,19] Indeed, the energy production related to lactate production was estimated to be at least 10% of the aerobic energy production at high-intensity submaximal exercise and could influence the V_{O_2MAX}.[2] The present results also confirmed that ΔP (i.e., the difference between P_{max} and V_{O_2MAX}) can be used to determine the working capacity above V_{O_2MAX} and is a better indicator of maximal anaerobic power and capacity than P_{max}.[20,23] Thus, in order to simplify the assessment of the effectiveness of the training program, v_{LT} and ΔP provide the best combination for testing distance runners.

Conclusion

The principal component analysis appears as a reasonable approach for training intervention studies. The results of the present study suggest that the PCA can be a useful method to disentangle the aerobic and anaerobic components in testing procedures. It can reduce a large number of highly interrelated variables to a small number of independent factors, and therefore can better assess the effects of training on aerobic and anaerobic characteristics. Thus, further investigations are needed to identify, by using a multivariate approach, the key physiological factors of the running performance from 800-m to marathon.

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Practical implications

- The maximal anaerobic running test (MART) is a practical track test to measure the anaerobic running capacity of middle-distance runners.
- The track version of the MART is a sensitive test method to evaluate the effects of interval training.
- The velocity at the lactate threshold (v_{LT}) and the capability of the runner to product power above V_{O_2MAX} ($\triangle P$) are the best predictors of training effects in the group of middle-distance runners.
- An exhaustive running test run (T_{max}) at the lactate threshold (v_{LT}) + 50% of the difference between v_{LT} and the velocity associated with V_{O_2MAX} can be use as a pre-requirement to evaluate specific adaptation of runners on the track and to control the effectiveness of interval training programs.

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