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# Could middle- and long-distance running performance of well-trained athletes be best predicted by the same aerobic parameters?

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ABSTRACT

The prediction of running performance at different competitive distances is a challenge, since it can be influenced by several physiological, morphological and biomechanical factors. In experienced male runners heterogeneous for maximal oxygen uptake ($VO_2$max), endurance running performance can be well predicted by several key parameters of aerobic fitness such as $VO_2$max and its respective velocity (v$VO_2$max), running economy, blood lactate response to exercise, oxygen uptake kinetics and critical velocity. However, for a homogeneous group of well-trained endurance runners, the relationship between aerobic fitness parameters and endurance running performance seems to be influenced by the duration of the race (i.e., middle vs. long). Although middle-distance and ultramarathon runners present high aerobic fitness levels, there is no accumulating evidence showing that the aerobic key parameters influence both 800-m and ultramarathon performance in homogeneous group of well-trained runners. The v$VO_2$max seems to be the best predictor of performance for 1500 m. For 3000 m, both v$VO_2$max and blood lactate response to exercise are the main predictors of performance. Finally, for long distance events (5000 m, 10,000 m, marathon and ultramarathon), blood lactate response seems to be main predictor of performance. The different limiting/determinants factors and/or training-induced changes in aerobic parameters can help to explain this time- or distance-dependent pattern.

## 1. Introduction

Running exercise performance is a multifactorial phenotype (Joyner and Coyle, 2008; Thompson, 2017) and can be influenced by different aspects such as anthropometric (Maldonado et al., 2002), morphological and neuromuscular characteristics (Noakes, 1988; Paavolainen et al., 1999), energy supply and utilization (Gonzalez-Alonso and Calbet, 2003), biomechanical (Folland et al., 2017), motivational and sociological factors (Iso-Ahola, 1995), and thermoregulatory responses (Joyner and Coyle, 2008; Maughan, 2010). Therefore, the prediction of running exercise performance is a daunting task, since the percentage contribution of these aspects to success during running events seems also be influenced by factors such the duration of the race (i.e., short *vs.* middle *vs.* long), performance level and gender. However, there are several lines of evidence indicating that endurance running performance (i.e., from 800 m to ultra-marathons), can be well predicted by several key parameters of aerobic fitness (Lacour et al., 1990a; Craig and Morgan, 1998a). It is important to note that, the majority of the energy supply during these competitive events is derived through oxidative metabolism (Spencer and Gastin, 2001). This information is crucial for coaches and exercise physiologists to elaborate the evaluation processes (e.g., appropriated exercises tests) and training prescription (e.g., exercise intensity and duration).

The key parameters of aerobic fitness that can affect the endurance running performance are the maximal oxygen uptake ($VO_2$max) (Joyner and Coyle, 2008; Noakes, 1988; Noakes et al., 1990a) and its respective velocity (v$VO_2$max) (Lacour et al., 1990a; Noakes et al., 1990a), running economy (RE) (Conley and Krahenbuhl, 1980a), blood lactate response to exercise (Farrell et al., 1979; Sjodin and Jacobs, 1981), oxygen uptake kinetics (Millet et al., 2011; Farrell et al., 1979; Ferri et al., 2012), and critical velocity (CV) (Noakes, 1988). The $VO_2$max, which reflects an individual's maximal rates of oxygen utilization and v$VO_2$max are both obtained during ramp or incremental exercise test. While $VO_2$max values are protocol-independent, v$VO_2$max determination is method (e.g., a) minimal velocity at which $VO_2$max occurred; b) solving the regression equation describing the relationship between $VO_2$ and submaximal exercise intensity for $VO_2$max, and; c) the highest velocity attained in the ramp incremental test) and protocol-dependent (i.e.,

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ramp slopes or step increase and duration) (Hill and Rowell, 1996; Morton, 2011). RE can been defined as the oxygen uptake required at a given absolute exercise intensity and has been determined during submaximal running protocol lasting 5–8 min (Guglielmo et al., 2009). Several biomechanical (e.g., gait patterns, kinematics and the kinetics of running) (Svedenhag and Sjodin, 1984) and physiological factors (e.g., oxidative muscle capacity) (Pate et al., 1992) and anthropometric characteristics (e.g., leg mass and distribution of mass) (Pate et al., 1992) seem to influence RE in well-trained athletes (Saunders et al., 2004; Barnes et al., 2015). The ability to exercise for long periods at high fractions of the $VO_2$max is associated with blood lactate response to exercise (Costill, 1970). Blood lactate response during incremental exercise has been used to identify the lactate threshold (LT) (the running speed associated with the first and sustained increase in blood lactate) (Carter et al., 2000), while the protocol traditionally utilized for the determination of maximal lactate steady state (the highest blood lactate concentration that can be identified as maintaining a steady-state during prolonged submaximal constant workload - MLSS) is generally constituted by a series of 30-min constant-intensity trials, performed in different days (Beneke et al., 2003). It is important to note that, in well-trained runners, LT and MLSS are identified at different exercise intensities (60–70% $VO_2$max and 85–95% $VO_2$max, respectively) and should not be used interchangeable (Noakes, 1988). Moreover, some studies have used indirect indexes to estimate both LT (ventilatory threshold - VT) (Cerezuela-Espejo et al., 2018) and MLSS [onset blood lactate accumulation – OBLA (Denadai et al., 2005), lactate turnpoint – LTP (Smith and Jones, 2001), velocity at 4 mM blood lactate concentration - V4 (Heck et al., 1985), respiratory compensation point – RCP (Laplaud et al., 2006). At the onset of high intensity exercise the oxygen uptake kinetics dictates the rate at which $VO_2$ increases to meet the energy demands and, consequently, the exercise tolerance. Indeed, some interventions (e.g., priming exercise) that are used to improve $VO_2$ kinetics can reduce the magnitude of the $O_2$ deficit during the initial phase of exercise, improving performance during high-intensity exercise (Carita et al., 2014). The critical power/critical velocity (CP/CV) has been also used as a robust parameter of aerobic fitness. CP/CV corresponds to the asymptote of the hyperbolic relationship between exercise intensity and time to exhaustion (Jones et al., 2010). CV has been defined as the highest velocity that can be sustained without exhaustion (Monod and Scherrer, 1965), and corresponds to the highest rate of oxidative metabolism that can be sustained (Jones et al., 2010). Thus, peripheral aspects related to the aerobic energy production are the main determinants of CV.

## 2. Aerobic fitness parameters and training effects

Endurance training and strength training can determine important modifications on the key parameters of aerobic fitness. The magnitude of this modification is mainly dependent of interaction between training load (intensity x duration x weekly frequency) and initial aerobic fitness level (Joyner and Coyle, 2008). It has been shown that endurance submaximal training and high-intensity interval training (HIT) did not improve $VO_2$max of well-trained endurance runners (Denadai et al., 2006). However, the $vVO_2$max can be increased using HIT (Denadai et al., 2006) or adding traditional strength training to the training routine (Guglielmo et al., 2009), which contribute to explain the performance improvements in these athletes. There is some evidence that HIT (Denadai et al., 2006) or heavy-resistance strength training (i.e., ~90% one-repetition maximum) (Guglielmo et al., 2009) added to regular endurance training can improve RE in well-trained endurance athletes after short training period (i.e., 4 weeks). Different biomechanical and physiological factors seem to influence RE in trained athletes (Saunders et al., 2004; Barnes et al., 2015). Specifically, neuromuscular characteristics (i.e., mechanical and morphological properties of muscle-tendon unit, motor units recruitment pattern, muscle fiber distribution) influence RE and can be modified after HIT or traditional strength training (Guglielmo et al., 2009; Denadai et al., 2006)). This improved RE can explain, at least in part, the modification of $vVO_2$max after short training period of HIT (Denadai et al., 2006) or traditional strength training (Guglielmo et al., 2009). Indeed, the $vVO_2$max reflects the association between $VO_2$max and RE. However, the $vVO_2$max is also influenced by anaerobic capacity and neuromuscular characteristics (Denadai and Greco, 2018). Thus, it is possible that $vVO_2$max can be modified without changes in RE. In fact, Ronnestad et al. (2015) found in elite cyclists that the Wmax (i.e., the mean power output during the last 2 min of the incremental test) was increased after heavy strength training, while no significant change was observed in $VO_2$max and gross efficiency. The improvement of blood lactate response to exercise after an endurance training program of relative short duration (6–8 weeks) is often associated with physiological adaptations of a peripheral nature (e.g., increased muscular capillary density and muscular blood flow, enhanced size and number of mitochondria per unit area) (Daussin et al., 2007). Although these peripheral adaptations are likely to contribute to improvements in $VO_2$max, a greater improvement in both LT and MLSS have been demonstrated during long-term training programs due to the attainment of a $VO_2$max ceiling (Jones and Carter, 2000). In addition to the increase in the velocity associated with LT and MLSS (vMLSS), the relative intensity (i.e., %$VO_2$max) at which these indexes are attained is also higher after a long period of training (i.e., 70% and 95%, respectively), so that these athletes can run at high fractions of $VO_2$max for long-duration events. Therefore, a higher submaximal intensity may be necessary in trained athletes for further improvement in LT and MLSS (Londeree, 1997). This is similar for CV, which is also attained at high percentage of $VO_2$max in highly trained athletes (Jones and Vanhatalo, 2017).

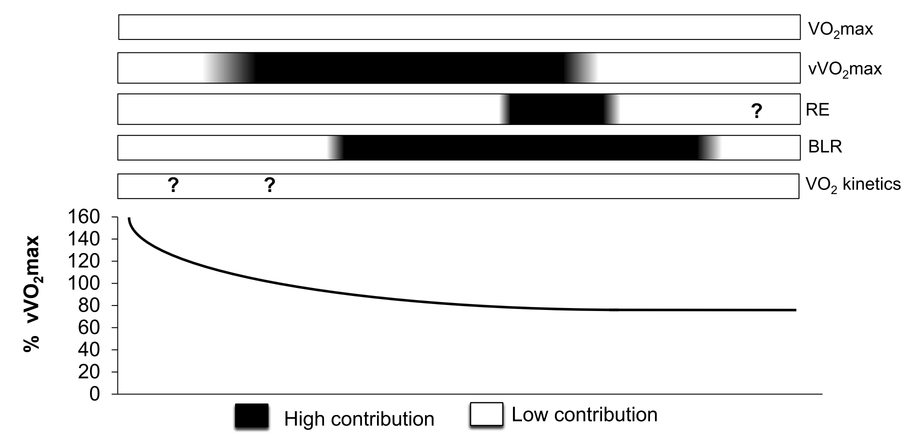
## 3. Aerobic fitness parameters and endurance running performance

The analyses of percentage contribution to endurance running performance of the different key parameters of aerobic fitness have been done mainly by cross-sectional design (i.e., correlations analyses and multiple regression analyses). This approach is interesting but can present some limitations. The main problem is that the strength of a predictor variable in a regression equation can be influenced by the homogeneity of the variables analyzed. Thus, caution is necessary when some correlational analyses are compared. Longitudinal studies (i.e., randomized controlled trials) performed in well-trained runners are an excellent design, but few studies have been conducted. Some studies performed in well-trained runners are summarized in the next paragraphs aiming to fundament the model presented in Fig. 1.

**800 m** – No single key aerobic parameter has been found to be associated with 800 m performance in homogeneous groups of well-trained runners (Lacour et al., 1990b; Craig and Morgan, 1998b). Similarly, the 800-m running performance was not significantly correlated with anaerobic capacity (e.g., accumulated oxygen deficit - AOD) and $VO_2$ kinetics during supramaximal exercise (110% $vVO_2$max) (Craig and Morgan, 1998b; Denadai et al., 2004).

**1500 m** – Several cross-sectional studies have demonstrated that $vVO_2$max is the best predictor of the 1500 m performance in well-trained runners (Lacour et al., 1990b; Denadai et al., 2004; Billat et al., 1996). Indeed, longitudinal studies have confirmed that 1500-m was improved after HIT only when $vVO_2$max was increased (Denadai et al., 2006). Interestingly, 1500-m race distance elicits anaerobic metabolism to its maximum capacity. However, an indicator of anaerobic capacity (i.e., AOD) and $VO_2$ kinetics during maximal exercise (100% $vVO_2$max) seems not predict the 1500 m running performance (Ferri et al., 2012).

**3000 m** – In homogeneous groups of well-trained runners, $vVO_2$max, blood lactate response to exercise (i.e., V4) and CV were correlated with 3000-m performance (Lacour et al., 1990a; Bragada et al., 2010). Interestingly, the predictive power of $vVO_2$max and V4 was very similar.

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|---|---|---|---|---|---|---|---|
| Duration (min) | 1.7-1.9 | 3.5-3.8 | 8.3-8.8 | 13-14 | 27-28 | 130-150 | 480-780 |
| Event | 800 m | 1500 m | 3000 m | 5000 m | 10000 m | Marathon | Ultraendurance |
| % $vVO_2max$ | 125-130 | 110-115 | 100-105 | 95-97 | 90-95 | 75-80 | 50-70 |
| % $VO_2max$ | 90-100 | 95-100 | 93-95 | 90-95 | 85-90 | 70-75 | 45-60 |
| Aer/An % | 65/35 | 75/25 | 85/15 | 90/10 | 100/0 | 100/0 | 100/0 |

**Fig. 1.** Bottom panel: Schematic illustration of the effect of race distance on the time to complete the race. Top panel: Schematic showing the contribution of key aerobic parameters to endurance running performance of well-trained athletes. Note that in the intermediary events (from 1500-m to marathon), a time- or distance-dependent pattern can be observed. See text for detailed explanation. $VO_2max$ - maximal oxygen uptake; $vVO_2max$ - velocity at $VO_2max$; RE - running economy; BLR - blood lactate response; $VO_2$ kinetics - oxygen uptake kinetics; Aer/An % - percentage contribution of anaerobic and aerobic systems.

This result was confirmed after a training period, where changes in both $vVO_2max$ and V4 explained changes in 3000 m running performance (Bragada et al., 2010).

**5000 m** – Several studies conducted in well-trained runners have reported a high correlation between blood lactate response (V4) to exercise and 5000 m performance (Paavolainen et al., 1999; Denadai et al., 2004). Similar results have been found between $vVO_2max$ and 5000 m performance (Lacour et al., 1990a). However, studies that have employed multiple regression analyses found that blood lactate response to exercise (V4 and RCP) was the main predictor of 5000 m running performance (Paavolainen et al., 1999; Denadai et al., 2004).

**10,000 m** – Blood lactate response to exercise (LT and V4) and CV presented high correlation with 10,000 m running performance (Sim õ es et al., 2005; Kumagai et al., 1982; Santos-Concejero et al., 2014; Kranenburg and Smith, 1996). Moreover, Tanaka et al. (1986) verified after a 4-month period of intensive training that the change in $VO_2$ at LT was significantly related to the change in the 10,000 m run time. In well-trained runners with similar $VO_2max$ values, RE (Conley and Krahenbuhl, 1980b) and $vVO_2max$ and V4 (Morgan et al., 1989) were significantly related with 10,000 m running performance.

**Marathon** – Using similar study designs (i.e., multiple regression analyses), Farrell et al. (1979) and Sjodin and Jacobs (1981) have found that LT and OBLA accounted for 92–96% of the variation in marathon running velocity, respectively. In specialist marathon runners, Noakes et al. (1990b) found that velocity at LTP ($r = 0.93$) was a better predictor of marathon performance when compared to $vVO_2max$ ($r = 0.88$). Moreover, multiple linear regression showed that velocity at LTP accounted for approximately 50% of the variation in marathon race time.

**Ultraendurance** - Few studies have investigated in well-trained runners the possible influence of the aerobic parameters on ultra-endurance running performance. Noakes et al. (1990b) verified in ultra-marathon specialists that $vVO_2max$ ($r = 0.83$) and blood lactate response to exercise (LTP - $r = 0.80$) were significantly correlated with performance during 90 km ultra-marathon. Interestingly, $VO_2$ at 16 km/h was not significantly correlated with 90 km ultra-marathon time. However, the results of this study must be analyzed with caution, since the heterogeneity of both $VO_2max$ (53–78 ml $kg^{-1}$. $min^{-1}$) and performance time (345–592 min) can influence the correlation between dependent and independent variables.

## 4. Conclusion and avenues for future research

To analyze appropriately the model presented in Fig. 1, it is important to highlight some important aspects: a) as previously stated, endurance running performance is also influenced by anthropometric, neuromuscular characteristics, anaerobic energy supply, and thermoregulatory responses, and; b) there is no unique key parameter of aerobic fitness that may predict the endurance running performance. Bearing all of this in mind, it seems to be possible to identify for some events (from 1500 m to marathon) the best aerobic parameters related with endurance running performance in homogeneous group of well-trained runners. Although middle-distance and ultramarathon runners present high aerobic fitness level (Boileau et al., 1982; Garbisu-Hualde and Santos-Concejero, 2020), there is no accumulating evidence showing that the same aerobic key parameters influence both 800-m and ultramarathon performance in homogeneous group of well-trained runners. Thus, more studies using multiple regression analyses and training interventions in well-trained runners are necessary to identify possible variables (e.g., $VO_2$ kinetics for 800-m and RE and thermoregulatory responses for ultramarathon) that can influence the performance in these events. There is some evidence indicating that $VO_2max$, $vVO_2max$, running experience and cost of transport (Garbisu-Hualde and Santos-Concejero, 2020), as well as age and gender (Renfree et al., 2016) are key determinants of ultra-marathon performance. Additionally, thermoregulatory responses (Brown and Connolly, 2015), nutritional aspects (Nikolaidis et al., 2018), gastrointestinal distress (Stuempfle et al., 2013) exercise-associated hyponatremia and dehydration (Hoffman MD Injuries and health considerations in ultramarathon runners, 2016), as well as overuse injuries (Hoffman MD Injuries and health considerations in ultramarathon runners, 2016) can also have significant influence on performance during these events. In the intermediary events (from 1500-m to marathon), a time- or distance-dependent pattern can be observed. The $vVO_2max$ seems to be the best aerobic parameter to predict endurance running performance during supramaximal events (i.e., 1500-m). During submaximal events (from 5000 m to marathon), blood lactate response to exercise seems to be the best aerobic index to predict endurance running performance. A "crossover" point seems to exist during maximal exercise (i.e., 3000-m), where endurance running performance can be predicted similarly by the $vVO_2max$ and blood lactate response to exercise. The different limiting/determinants factors and/or training-induced changes in aerobic parameters can help to explain this time- or distance-dependent pattern. $VO_2max$ and $vVO_2max$ are determined mainly by central aspects (i.e., cardiac output), while blood lactate response and CV are mainly determined by peripheral factors (i.e., oxidative capacity).

Aiming to improve our understanding about the determinants of endurance running performance, we invite cross-sectional and longitudinal studies to carefully analyze the model discussed above. Special attention should be given to the $vVO_2max$, since its determination is method- and protocol-dependent. Thus, the possible influence of this aspect to predict endurance running performance during cross-sectional and longitudinal studies must be investigated. Finally, the data discussed here are not necessarily applied to analyze the endurance running performance of world-class athletes. Nonetheless, there are many well-trained runners and professionals working with these athletes (e.g., coaches, exercise physiologists, academic researchers), who can apply the model discussed here.

## CRediT authorship contribution statement

**Benedito Sérgio Denadai:** Conceptualization, were involved in the conception and design of the study, Formal analysis, were involved in data collection, All authors were involved in the analysis and interpretation of the data, Writing – review & editing, as well as writing and revising the manuscript, All authors approved the final version of the manuscript and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved, All persons designated as authors qualify for authorship, and all those who qualify for authorship are listed. **Camila Coelho Greco:** L.H.P.A.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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