REVIEW ARTICLE

TRENDS in
Sport Sciences
2020; 27(**3**): 117-123
ISSN 2299-9590
DOI: 10.23829/TSS.2020.27.3-1

Physiological predictors of distance runners' performance: a narrative review

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Abstract
The main purpose of this article was to review and discuss the current literature on the following physiological parameters: maximal oxygen uptake (VO_2max), running economy (RE), running velocity at vVO_2max (vVO_2max), time limit at vVO_2max (tlimit), running velocity at lactate threshold (vLT) and maximal speed (Vmax) on running performance. Many coaches and trainers believed that athletes with higher VO_2max have better performance, but a lot of studies have shown that VO_2max is a poor predictor of endurance performance. Alternatively, RE, vVO_2max, tlimit, vLT and Vmax were shown to be superior predictors of distance running performance. Therefore, if researchers and coaches can improve the values of all five parameters, the calculations suggested that the runner would be able to complete a marathon in 1:57:58. In conclusion, this review provides some practical suggestions as how to improve the performance in distance runners.

KEYWORDS: physiological parameters, performance, distance runners.

Received: 26 June 2020
Accepted: 22 August 2020

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Introduction

Many physiological variables are associated with aerobic function and are used to determine running performance [9]. These are: maximal oxygen uptake (VO_2max), running economy (RE), running velocity at VO_2max (vVO_2max), time limit at vVO_2max (tlimit), running velocity at lactate threshold (vLT), and maximal speed (Vmax). The resulting question is which of these is the better predictor for performance in distance runners. It is very difficult to answer because studies use runners with different backgrounds and ability levels. It seems, however, that the most beneficial might be using the combination of several physiological factors to predict endurance performance in runners.

VO_2max is relatively homogeneous in elite runners, and within elite populations, race times were shown to have only a low to moderate correlation with VO_2max. For example, elite endurance athletes may have VO_2max values ranging between 70 and 85 $ml \cdot kg^{-1} \cdot min^{-1}$ [47]. Alternatively, physiological parameters like RE, vVO_2max, tlimit, vLT, and Vmax were shown to be superior predictors of distance running performance [1, 12, 20, 38]. The purpose of the current article is to discuss the role of VO_2max, RE, vVO_2max, tlimit, vLT, and Vmax and the significance of their implementation into distance runners' training. If the coaches or athletes consider the relevance of other physiological factors they will be able to maximize the running performance.

Maximal oxygen uptake (VO_2max)

VO_2max was first described by Hill and Lupton [28]. Over the following decades, VO_2max was accepted as a measure of the functional capacity of the cardiovascular system [27, 31, 46], and is taken as a measure of cardiorespiratory fitness. Average values in elite men long-distance runners range from 75 to 85 $ml \cdot kg^{-1} \cdot min^{-1}$,

and from 60 to 75 ml·kg^{-1}·min^{-1} in elite women long-distance runners [51, 54].
Paradoxically, there is a little relationship between VO_2max and race times among competitive long-distance runners [2]. A paradox is that a runner who improves VO_2max from 60 to 66 ml·kg^{-1}·min^{-1} can usually be assured of an approximate 10% improvement in performance, but a runner with a VO_2max of 66 ml·kg^{-1}·min^{-1} has no assurance that that is 10% better than a competitor with a VO_2max of 60 [2]. Studies have reported that VO_2max is a poor predictor of endurance performance when athletes of widely varying abilities are compared [34, 39, 41]. Legaz Arrese et al. [34] examined the relationship of VO_2max on performance in trained endurance runners. The results showed no relationship between changes in VO_2max and race performance. The study of Ramsbottom et al. [45] found that improvements in a 5 km trial were correlated with RE but not with VO_2max, while in the study by Paavolainen et al. [43] 5 km performance actually declined with improvements in VO_2max.

Training effects on VO_2max
Two of the most common endurance training strategies are interval training and continuous training methods [23]. The study of Pollock [44] has shown that improvement in VO_2max is directly related to intensity, duration, and frequency of training. The study by Helgerud et al. [27] revealed that the 15/15 (15-s intervals at 90-95% HRmax with 15 s of active resting periods) and the 4×4 min training (4×4-min interval training at 90-95% HRmax with 3 min of active resting periods at 70% HRmax between each interval) significantly increased the level of VO_2max in healthy students. However, long slow distance running (continuous run at 70% HRmax for 45 min) and lactate threshold running (continuous run at lactate threshold at 85% HRmax for 24.25 min) did not change their VO_2max. Another study [3] performed in young individuals with average cardiorespiratory fitness, shown that 20 sessions of periodized high volume interval training led to significant increases in VO_2max. Similarly, Gorostiaga et al. [24] when compared the effects of interval and continuous training programs on VO_2max showed that VO_2max was increased by 5% in the continuous training program, and 10% in the interval training program. The research clearly shows that continuous base training is an inefficient way to build an aerobic base and that the interval training improves VO_2max more effectively.

Running economy (RE)
Among the factors that may predict middle- and long-distance running performance, running economy (RE), commonly defined as the steady-state VO_2 required at a given submaximal speed, has gathered the most attention over the last decade, although it is often still referred to as "being relatively ignored in the scientific literature" [4]. In the last decades, the researchers have focused on measuring RE in distance runners and many studies have found a strong association between RE and race performance. Some studies indicate that RE is an even better predictor of race performance among elite runners than VO_2max [16, 39, 47, 48].
Runners with good RE use less oxygen to run at a specific velocity compared to runners with less optimal economy [2]. When comparing two runners with similar VO_2max values the runner with better RE will achieve better performance time. Kenyan and Ethiopian runners have dominated middle- and long-distance running events compared to European runners. The runners from Africa do not have a higher VO_2max compared to European runners, but they have better performance [58]. The explanation is that African runners are typically smaller even compared to other elite runners, and studies have shown that smaller runners and runners with thinner and shorter lower limbs have better RE [14].
RE is a strong predictor for performance [32] because a runner with a greater economy will tend to work at lower percentages of VO_2max for various speeds than a runner who requires more oxygen and therefore has a poor economy [2]. For example, if two runners in a race have the same pace but one runner's oxygen-consumption rate is 80% of VO_2max while the second runner's oxygen-consumption rate is 90% of VO_2max, the first runner will continue the race for a greater distance than the second one. More specifically the first runner has greater RE than the second.
Numerous studies have examined the effects of RE in distance runners' performance and found a strong association between RE and race performance. More specifically, Di Prampero et al. [18] reported that a 5% increase of RE induced a 3.8% increase in distance running performance. Weston et al. [57] investigated the RE and 10 km performance in African and Caucasian distance runners. African and Caucasian runners had similar race times in 10 km, but the African runners had a 13% lower VO_2max, but 5% better RE than Caucasians. This study indicates a greater RE and higher fractional utilization of VO_2peak in African distance runners. The study of Conley and Krahenbuhl [15] determined the relationship between RE and distance running performance in highly trained and experienced distance runners. All runners had similar VO_2max and within this elite cluster of finishers, 65.4% of the variation

observed in race performance time on the 10 km run could be explained by variation in RE.

On the other hand, only a few studies suggested that RE was not associated with running performance in competitive distance runners. Mooses et al. [39] suggested that in the homogenous group of Kenyan distance runners, RE can be compensated for by other factors (such as VO_2max) to maintain high-performance levels. Similar results are found in the study of Grant et al. [25] who reported that neither VO_2max nor RE was strongly correlated with the performance of 3 km. They also reported that vLT plays an important role in a 3 km running performance.

A variety of training strategies have been adopted in an attempt to improve RE. The most common training factors for improving RE are strength training (plyometric), tapering, hill, and pace-specific training (Figure 1).

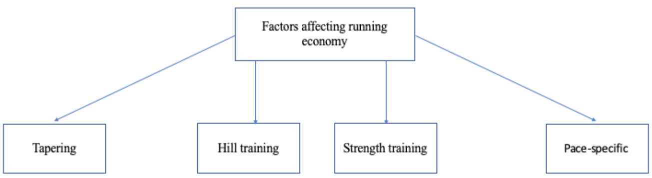

Figure 1. Training factors for improving running economy

Strength training

RE improvements, as a consequence of strength training interventions, have been attributed to improved lower limb coordination and muscle coactivation, which would ultimately increase muscle stiffness and decrease ground contact times [35]. A meta-analysis published by Balsalobre-Fernández et al. [4] examined the effects of strength training on RE in highly trained distance runners. Authors reported that a strength training program including low to high-intensity resistance exercises and plyometric exercises performed 2-3 times per week for 8-12 weeks was an appropriate strategy to improve RE in the highly trained middle- and long-distance runners. The study by Li et al. [35], demonstrated improvement in RE and performance of 5 km running after complex training, which included a back squat + a drop jump from a 40 cm box; a Bulgarian split squat + a single leg hop; and a Romanian deadlift + a double leg 50 cm hurdle hop. Similarly, the study by Støren et al. [55] reported that maximal strength training for 8 weeks improved RE by 5.0% among well trained, long-distance runners, without a change in maximal oxygen uptake or body weight. Sedano et al [50] indicated that 12 weeks of combined and plyometric training lead to improve RE. Paavolainen et al. [43] showed that 9 weeks of explosive-strength training improved RE (8%) and 5 km performance (3%) in moderately trained runners. The study by Saunders et al. [49] reported that in a group of highly-trained distance runners, 9 weeks of plyometric training improved RE by 4.1%, with likely mechanisms residing in the muscle, or alternatively by improving running mechanics. In a study of Blagrove et al. [13], ten weeks of strength training (2 days/week) added to the program of a postpubertal distance runner was highly likely to improve maximal speed and enhance RE by 3.2-3.7%. The study of Beattie et al. [7] demonstrated that 40 weeks of strength training can significantly improve maximal and reactive strength qualities, and RE by 5.0% in distance runners.

Tapering

Tapering is the reduction in training load before the competition or the final period before a major competition and it is very important for the athlete's performance. The aim of tapering is to maximize physiological adaptation with the reduction of accumulated fatigue [26]. Only 3 studies examined the effects of tapering on RE. The study of Houmard et al. [30] indicates that 7 days of tapered running improved distance running performance and RE by 6% in a group of well-trained endurance runners. In another study [52] RE at 60% vVO_2max was improved after 16 days of tapering. It is in agreement with the study of Houmard et al. [29] who investigated the effects of tapering on RE at 85% VO_2max speed after 2 and 3 weeks of taper and at 65% VO_2max after 3 weeks of taper.

Hill training

Hill training is another strategy that enhances RE. Only one study examined the effects of six-week hill training on RE in distance runners and showed its improvement by 2.4% ± 1.4% [5].

Pace-specific training

Tempo runs are believed to enhance RE at the chosen training speed. Indeed, the study of Paavolainen et al. [43] suggested that muscle power may influence RE both at submaximal velocities and most probably at race pace. However, the study of Beneke and Hütler [8] indicated that training tends to improve economy the most at specific speeds used during training. This has important implications for the overall construction of a training plan. Moreover, 5 km runners should include a significant amount of training at the goal 5 km pace in order to optimize the economy at their desired intensity, and marathoners should insert segments paced at their marathon goal speeds into their long runs and tempo runs [12].

Running velocity at VO_2max (vVO_2max)

vVO_2max it is the minimum running velocity that elicits a runner's maximal rate of oxygen consumption or VO_2max [2]. Some studies suggest that vVO_2max is the best predictor of running performance [17]. vVO_2max combines VO_2max and RE into a single factor and explains differences in performance that VO_2max or RE alone cannot [25]. The study of McLaughlin et al. [38] showed that among well-trained subjects − heterogeneous in VO_2max and running performance − vVO_2max is the best predictor of running performance because it integrates both maximal aerobic power and the RE. Morgan et al. [40] reported that there is a strong relationship between vVO_2max and 10 km run time. Data from this study also suggest that vVO_2max may be potentially useful as an index of training status and a sensitive, noninvasive predictor of distance running performance. McCormack et al. [37] reported that vVO_2max was the best predictor of 3 km race performance in a group of collegiate distance runners with heterogeneous VO_2max values. A study by Slattery et al. [53] showed similar results and explain that close relationship between vVO_2max and 3 km race time may be due to the fact that middle distance races are completed at a velocity similar to that of VO_2max, whereas velocities of longer distance races are closer to lactate threshold, and therefore vVO_2max may become a better predictor of performance in the middle-distance events.

On the other hand, Grant et al. [25] found that vVO_2max was the third-best predictor of 3 km run performance behind vLT and velocity at 4 mmol of blood lactate. According to Emerick et al. [19], this study failed to support the use of vVO_2max as the best predictor of marathon performance in a group of recreational female runners. The study reinforced the notion that VO_2max combined with weekly training distance elicits the best prediction of marathon performance. These findings suggest that recreational female runners should focus on increasing their VO_2max and increasing their total training distance to improve their marathon performance. Endurance runners, coaches, and exercise physiologists gained the notion of why vVO_2max is a much more useful performance predictor in distance running than VO_2max. The latter contains no information about an athlete's RE. In case of a runner with high VO_2max and low levels of RE, his performance could be disappointingly slow despite the high aerobic capacity [2].

Time limit at vVO_2max

The time limit at vVO_2max (tlimit) is also important for distance running performance and is a sister measurement of vVO_2max. To determine the time limit at vVO_2max the athlete runs at 100% of vVO_2max until exhaustion, without slowing the pace or stopping. Direct measurement of tlimit indicates that it ranges from 150 s to 10 min and cannot last longer than 20-25 min [11, 33]. Billat [10] showed that the time limit at vVO_2max was on average 6 min. Tlimit has a practical application in endurance athletes, for example, if two runners have similar values of vVO_2max, the runner with higher tlimit will win the race.

Running velocity at lactate threshold (vLT)

Determining lactate threshold (LT), defined as the point at which blood lactate concentration increases exponentially with increasing exercise intensity, has been used to ascertain endurance capability, measure adaptations to training, and to predict performance potential [22]. Furthermore, LT is considered a valid performance indicator as there are strong linear correlations with endurance performance [21].

Running velocity at lactate threshold (vLT) is simply the velocity above which lactate begins to accumulate in the blood. Like RE and vVO_2max, vLT is a strong physiological predictor of endurance performance [6]. Many coaches and researchers try to move the vLT to progressively faster speeds. Having a high vLT means that a runner can process pyruvate at greater rates and thus has the energy needed to run fast and long during endurance competitions [2].

In athletes with several years of training experience, VO_2max may not improve any more, but vLT might increase by 3-10% depending on the chosen training program. It has been observed that individuals with similar VO_2max have variability in endurance capacity and that highly trained athletes usually perform at a high percentage of their VO_2max with minimum lactate accumulation [56, 59]. Furthermore, trained athletes accumulate less lactate than untrained athletes at a given submaximal workload.

Maximal speed (Vmax)

The study by Noakes et al. [42] was the first to report that maximal speed was a strong determinant of endurance performance. This study showed that peak treadmill velocity was the best laboratory predictor of running performance at 10, 21.1, 42.2, and 90 km distances in ultra-marathon runners, and it was also the best predictor of running performance for 10 and

21.1 km distances in marathon runners. The results of the Slattery et al. [53] study, showed that Vmax was the single best predictor of 3-km running performance in experienced male triathletes and that both aerobic and anaerobic abilities are related to improved 3 km time trial performance. Since the assessment of Vmax is relatively simple to implement, we suggest that determining Vmax could be a practical method for monitoring performance changes in short-term endurance running events. The study of Paavolainen et al. [43] provides strong evidence that explosive training improves maximal running velocity and that the increases in maximal speed are closely coupled with improvements in endurance performance. This study examined 18 athletes who ran an all-out 20-meter sprint and a 5 km race (as fast as possible) on an indoor track. After 9 weeks the explosive-trained runners noted a 3% improvement and were 30 seconds faster in the 5 km event. Manoel et al. [36] compared the effects of 4 weeks of Vmax or vVO_2max training in endurance runners. The results showed a significant effect of training on Vmax and 10 km performance. It was concluded that Vmax training promoted similar improvements as the training that included vVO_2max.

Conclusion

Many coaches and trainers believed that athletes with higher VO_2max have better performance. Many recent studies have shown that VO_2max alone is rather a poor predictor of endurance performance. It seems that actually, besides VO_2max, the physiological factors that are associated with aerobic capacity are RE, vVO_2max, tlimit, vLT, and Vmax.

Conflicts of interest

The authors declare no conflict of interest.

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