REVIEW ARTICLE

Lactate threshold training to improve long-distance running performance: A narrative review

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Abstract

This narrative review revealed the crucial aspects that need to be highlighted when introducing the lactate threshold (LT) training protocol to improve the distance running performance of athletes. The authors searched Google Scholar, Scopus, PubMed and categorized the search results into nine themes. These aspects include the physiology of LT training, the individualization of LT training programs, the effects of the LT training protocol on endurance performance, the practical application of LT training for distance runners, progress monitoring and LT training adaptation, and the role of nutrition and recovery in LT training, the role of artificial intelligence in LT training, possible drawbacks and remedial strategies, and future directions in LT training research. This review suggests improving endurance through improving muscle lactate utilization and highlights the need for individualization of LT training programs, taking physiological variations and psychological factors into account to effectively tailor training. In particular, physiological adaptations such as improved metabolic efficiency and lactate clearance contribute to longer time to exhaustion and longer overall athletic performance. Additionally, the author covers structured training, pacing strategies, and real-world considerations such as terrain and altitude necessary for training long-distance runners. Finally, it is important to monitor progress and adjust LT training protocols based on physiological markers, performance indicators, and environmental factors. Possible disadvantages such as overtraining and injury risks are discussed, as well as strategies to limit damage through regular assessments and biomechanical analysis. This review covers key aspects of LT training and provides insights for athletes and coaches to optimize programs, improve performance, and guide future research.

Keywords: *Anaerobic Threshold, Exercise Training, Distance Running, Artificial Intelligence, Athletes*

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Introduction

Distance running is a demanding sport that requires careful training and preparation to achieve peak performance. In particular, long-distance running, including marathons and ultramarathons, pose significant physiological challenges and the ability to effectively manage and utilize lactate is critical (Denadai and Greco, 2022). Lactate threshold (LT) is an important physiological marker of long-distance running performance, and LT training has become a cornerstone of endurance training (Støa et al., 2020). Therefore, the LT protocol has gained considerable attention in the field of endurance training as a potential method to improve distance running performance (Casado et al., 2022). The emphasis is on training at or around lactate threshold, the point at which lactate production exceeds the body's ability to remove it, ultimately leading to improved endurance and faster race times (Stoa et al., 2020). While much remains to be understood about the exact mechanisms behind the LT protocol, numerous studies have demonstrated its effectiveness in improving distance running performance (Casado et al., 2022). During exercise, lactate is constantly produced as a byproduct of glucose metabolism. However, the body has mechanisms to remove lactate from the circulation and use it as an energy source. As exercise intensity increases, lactate production also increases, leading to gradual accumulation in the bloodstream. The LT is the exercise intensity at which lactate production exceeds its clearance capacity, resulting in a significant increase in blood lactate concentration (Goodwin et al., 2007). This phenomenon is closely related to fatigue and loss of performance during prolonged endurance training, which are due to the accumulation of lactic acid (Emhoff and Messonnier., 2023; Yang et al., 2020). In addition, several studies have provided evidence for the concept of lactate threshold, which refers to the exercise intensity at which lactate accumulates faster than it can be cleared from the bloodstream (Goodwin et al., 2007; Ghosh., 2004). These key findings laid the foundation for subsequent research into lactate threshold and its effects on exercise performance and training. (Faude et al., 2009)

Overview of Lactate Threshold Protocol

The LT protocol plays a central role in training and performance optimization for endurance athletes. It represents a crucial physiological marker that describes the transition from aerobic to anaerobic metabolism during exercise (Ghosh., 2004). The LT marks the point at which lactate production exceeds its clearance, contributing to fatigue and a shift toward anaerobic metabolism (Faude et al., 2009). Improved lactate clearance rates during LT training delay the onset of fatigue, especially during longer runs (Nuuttila et al., 2022). Furthermore, LT training leads to adjustments in muscle fiber recruitment patterns, thereby optimizing endurance performance (Bassett & Howley, 2000). In particular, LT training leads to metabolic adaptations, thereby improving the ability to utilize oxygen and sustain high-intensity efforts (Alejandro Lucía et al., 2000). LT is measured using the blood lactate threshold and is one of the most common methods that includes measuring blood lactate levels during incremental exercise tests (Billat, 2001) as well as the use of ventilation parameters such as ventilator equivalent for oxygen (Gouw et al., 2022). By understanding the concept of LT and its influence on distance running performance, athletes and coaches can tailor their training protocols to specifically target and improve this important physiological parameter. Therefore, the authors conduct this narrative review to highlight the critical aspects of LT protocol training and its impact on distance running performance.

Materials and methods

Search Strategy

This study presents a narrative review of the literature on two main objectives: the critical components of the LT protocol and its impact on long distance running performance. Electronic databases such as Google Scholar, PubMed and Scopus. The electronic search was conducted using MeSH (Medical Subject Headings) keywords appropriate to the current topic: "lactate threshold," 'anaerobic threshold," "exercise training," "distance running," "artificial intelligence," "athlete" to broaden and narrow the search.

Data extraction

The authors applied a series of inclusion and exclusion criteria to identify eligible articles and extract relevant data. Original articles, review articles and conceptual papers published

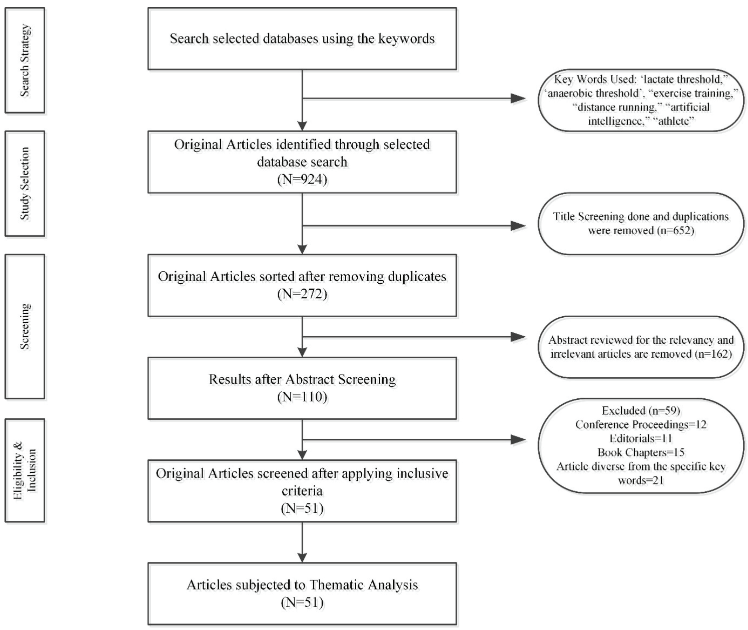

Figure 1. Flowchart showing the article retrieving process

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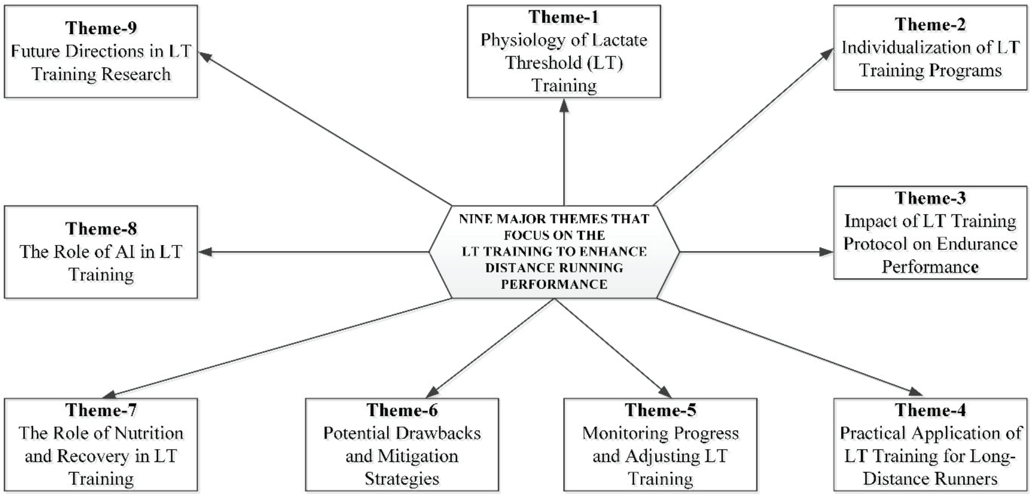

Figure-2: Themes that focus on the LT Training to enhance distance running Performance

between 2007 and July 2023 and written or available in English were included in the thematic analysis. In contrast, abstracts, conference proceedings, editorials, book chapters, and articles that deviated from the specific keywords were excluded. The authors also excluded works that were not available in English and were published before or after the specified time period. After applying these criteria, 924 publications were then retrieved. As a part of the title screening, 272 publications were sorted after removing duplicates. In addition, the abstracts of these selected publications were reviewed for relevance and 162 irrelevant publications were removed, leaving 110 publications. Among them, 59 publications (including abstracts, conference proceedings, editorials, book chapters, and articles deviating from the specific keywords) were excluded. Finally, 51 publications were selected and included in the thematic analysis phase (Figure 1). Specifically, the publications were reviewed in two steps. In the first phase, the authors reviewed the title and abstract of each article and determined whether they were relevant or not. In the second step, only the relevant papers were assessed for their suitability. The authors adopted an inductive approach to organize findings into themes. Accordingly, the principal investigator extracted key texts and potential new lines of inquiry in the form of codes and combined them into nine themes based on the homogeneous information. The principal investigator discussed the emerging themes (n = 9) with other team members with a broader methodological and open disclosure perspective. The research team discussed all articles on each theme to ensure accuracy and eliminate researcher bias. In finalizing the nine themes, the team consciously sought to draw insights from the literature without allowing each member's professional background, experiences and prior assumptions to influence the outcome. The principal author independently reviewed all disputes and consensus was reached. Based on the extracted data following the screening process, nine themes emerged describing the critical aspects of the LT protocol and its impact on distance running performance (Figure 2).

Results

Table 1. Study Characteristics showing key findings mapped under nine themes of LT training.

S.No.	Author	Key Findings	Themes covered
1	Messonnier et al. (2013) [ED]	Lactate threshold (LT) means the level at which removal of endogenous lactate is restricted, though endurance training augments the volumes for lactate production and removal and clearance for higher absolute and relative workload.	Theme 1
2	Ferraz et al. (2022) [OA]	Aerobic fitness can be empirically measured in Beagle dogs through velocity corresponding to the visual LT (VLTv) and bi-segmented linear regression model LT (VLTBI).	
3	Goodwin et al. (2007) [RA]	Elevated blood lactate concentration may be a normal physiological response, though it may be a sign of hypoxemia or ischemia. Clinicians should understand blood lactate concentration responses and their transport, delivery, and analysis.	
4	Theofilidis et al. (2018) [RA]	Blood lactate dimensions evaluate the input of the anaerobic metabolism to energy expenditure. They also aid in understanding a sportsperson's resistance to fatigue during high-intensity workouts.	
5	Farrell et al. (2021) [OA]	Training intensity distribution was calculated by evaluating the duration spent in three intensity zones: low, moderate, and high intensity.	
6	MacInnis and Gibala (2017) [RA]	Interval training is an influential stimulus to provoke progress in mitochondrial content and VO2max.	
7	Hughes et al. (2018) [RA]	Nutrition and exercise are vital for the adaptations observed in the muscle phenotype with training.	
8	Nuuttila et al. (2022) [OA]	Individualized endurance training may cause more progress in running performance and upsurge the chance of increased response while reducing the incidence of poor responses to endurance training.	Themes 2, 3, 5, and 6
9	Lievens et al. (2020) [OA]	An athlete's muscle typology is a crucial performance influential factor in several sports. In humans, muscle fatigue is reliant on the composition of muscle fiber types.	Theme 2

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Table 1. Study Characteristics showing key findings mapped under nine themes of LT training.

S.No.	Author	Key Findings	Themes covered
10	Foster et al. (2017) [RA]	There was more interest in the internal training load, permitting improved titration of training loads in sportspersons of divergent ability given chances of assessment of heart rate, lactate, VO2, and power output.	Themes 2, 3, 4, 5, and 6
11	Hamlin et al. (2019) [OA]	Young elite athletes experiencing University education along with their competition and training loads were susceptible to more stress at specific times of the year, such as examinations and the pre-season and exam period.	Theme 2
12	Casado et al. (2023) [RA]	Lactate-guided threshold interval training enhances the calcium and adenosine monophosphate-activated protein kinase signalling pathways, thereby augmenting mitochondrial proliferation.	Themes 2, 3, 4, 5, 6, and 9
13	Furrer et al. (2023) [RA]	Implementing the training approaches to elite athletes depends on a "trial-and-error" basis, with the athlete and coach's knowledge and practices providing the bedrock for "post hoc" scientific research and investigation.	Themes 3 and 8
14	Stone et al. (2022) [RA]	Specificity has two main facets, i.e., strength-endurance continuum and adherence to principles of dynamic correspondence. Following the dynamic correspondence's values and norms can permit a more significant transfer from training to performance assessments.	Themes 3, 4, 5 and 6
15	Carrier et al. (2023) [OA]	The Garmin Fenix 6® provides precise measurements of VO2 max and LT in athletes and aids in reaching training verdicts.	Themes 3, 4 and 5
16	Mumux Mirani (2022) [RA]	Marathon runners involve training sessions that should be grounded on runners' physiologic dimensions and focused on the improvement of those dimensions.	Theme 4
17	Bossi et al. (2017) [OA]	Fast runners initiate lower relative intensities and show an additional uniform pacing strategy compared to slow runners.	
18	Moisey et al. (2022) [RA]	Intensive care unit survivors described suboptimal nutritional consumption with numerous factors impacting nutritional retrieval.	Theme 7
19	Impey et al. (2018) [CO]	A paradigm named "fuel for the work required' is presented. It is an illustration of a combination of train-low models whereby the obtainability of reduced carbohydrates meets the stresses of future training sessions.	
20	Phillips and Van Loon (2011) [RA]	High protein intake relies on caloric debt, which may be beneficial in stopping the loss of lean mass during energy-constrained times to increase fat loss.	
21	Sawka et al. (2007) [RA]	During exercise, electrolytes and carbohydrate-rich beverages intake can give paybacks greater than water alone at specific conditions. The main focus is to replace any fluid electrolyte deficit following exercise.	
22	Fullagar et al. (2015) [RA]	Deprived sleep quality and quantity could lead to an imbalance of the autonomic nervous system and provoke signs of overtraining syndrome. After sleep loss, rises in pro-inflammatory cytokines could encourage immune system dysfunction.	
23	Ortiz et al. (2018) [SR]	Active recovery sessions can improve physiological recovery through reduced muscular blood lactate levels, enhancing the athlete's performance.	
24	Macdonald et al. (2013) [OA]	Application of an acute session of self-myofascial release for the quadriceps muscle significantly improved the range of motion of the knee joint, deprived of a related discrepancy in muscle performance.	
25	Pickering and Kiely (2019) [RA]	Athletes have to be treated differently despite the potential difficulty of a personalized training process.	Themes 8 and 9
26	Chidambaram et al. (2022) [RA]	Artificial intelligence (AI) methods to process data from sensors can sense patterns in positional and kinematic information and physiological parameters. Thus, AI techniques can indicate how athletes can boost their performance. However, AI adoption in Sports medicine faces numerous challenges, though AI has promising sports-related tools.	Theme 8
27	Dijkhuis et al. (2018) [OA]	Machine learning (ML) is a feasible method to systematize personalized daily physical activity prediction. Coaching can offer accurate and timely data on the participants' physical activity due to the application of ML to the participant's behavior as often and accurately assessed via wearable sensors.	
28	Rahlf et al. (2022) [PLCT]	Runners could respond to augmented risk during routine training using wireless inertial measurement units and ML systems. Thus, they can be dynamically involved in reducing injury during running.	
29	Seshadri et al. (2019) [RA]	Wearable sensors assess posture, movement, injury, and biomechanical forces regarding safety and physical performance. They also evaluate pulse rate, sleep quality, and muscle oxygen saturation.	
30	Hammes et al. (2022) [RA]	Six challenges were recognized concerning applying AI in elite sports. Those include linking AI and elite sports, interpretable AI outcomes, data collection, robust predictive models, closing the "sense-model-plan-act" loop, and having control in the practitioners' hands.	
31	Bodemer (2023) [RA]	Implementing AI in sports training effectively improves training competence, enhances performance results, and supports injury prevention and rehabilitation. AI algorithms, namely computer vision and ML, are used to process data, offer real-time feedback, aid in making judgments, and develop personalized training plans.	

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Table 1. Study Characteristics showing key findings mapped under nine themes of LT training.

S.No.	Author	Key Findings	Themes covered
32	Bouchard et al. (2011) OA	Genomic forecasters of the Vo2max response over regular exercise give fresh targets for reviewing the nature of fitness and its variation to proper exercise.	Theme 9
33	Amann (2011) RA	During exercise under "normal" environments, the regulatory mechanism is effective; however, it might turn into a subsidiary in favor of extreme environmental effects like heat and severe hypoxia.	
34	Van Hoovels et al. (2021) P	Sweat wearable lactate sensors are used for the evaluation of sports physiology. Real-time sweat lactate assessments and other biomarkers permit training periods to be carefully supervised and modified.	
35	Andria Shimi et al. (2022) OA	The improvement in the goalkeeping task performance is equally observed under progressive and fixed-intensity circumstances.	
36	Guest et al. (2019) RA	Personalized nutrition targets to create additional active and inclusive nutritional and supplement recommendations. These recommendations are grounded on fluctuating, interrelating variables in an athlete's sports condition.	
37	Ahmetov and Rogozkin (2009) RA	36 genetic markers are related to athlete status, and 39 might describe a within-group variation of physical performance in retort to strength/endurance training.	
38	McGee and Walder (2018) RA	The critical control spot for gene expression responses is epigenetic regulation of gene expression in retort to ecological provocations.	
39	Urtats Etxegarai et al. (2021) OA	A ML grounded system correlated highly with the empirically observed athletes' LT. This system is an alternative approach to the conventional invasive LT assessments for recreational runners.	
40	Mukhopadhyay (2022) RA	Individualized sports-specific periodization is the foremost concern for demonstrating the best performance in contemporary sports.	Theme 6
41	Lorenz et al. (2010) RA	Periodization regarding strength training is effective in strength and conditioning among untrained and trained athletes with normal health status.	
42	Lorenz and Morrison (2015) CC	Periodization explains the partition of the training process into specific phases. The alteration of the parameters within phases, namely, load, repetitions, sets) are required to produce particular adaptations anticipated during a specific time.	
43	Yang (2019) RA	Cross-training substitutes the kind of exercises involved that decrease fatigue and avoid overuse syndrome.	
44	van der Worp et al. (2015) RA	History of injuries and usage of inserts/orthotics are causative factors for running injuries.	
45	Armstrong et al. (2022) RA	Management of overtraining syndrome persists indefinable as its typical difficulty, definitely individualized phenotype, and inherent determinant connections of several influencing aspects such as severe exercise drill, energy obtainability, and the athlete's genome.	Theme 6
46	Atakan et al. (2021) RA	Several physiological adaptations provoked by high-intensity interval training programs enhance exercise dimensions and metabolic well-being in normal and clinical individuals.	
47	Casado et al. (2022) SR	Highly trained and elite distance runners indicate the benefit of linear periodization models in which "training intensity distribution" and volume exist the same during the preliminary and pre-event duration.	
48	Kreher and Schwartz (2012) RA	Overtraining syndrome results from extreme exercise deprived of enough rest. This condition leads to perturbations of immunologic, neurologic, and endocrinologic systems, along with mood swings.	
49	Doherty et al. (2021) OA	Athletes should own a customized and multidimensional recovery strategy linking hydration, nutrition, sleep, and other mental and physiological features.	
50	Zhang et al. (2023) SR	Exercise programs with specific characteristics are more beneficial in improving mental health than interventions with various types, frequencies, and durations.	
51	Park and Jeon (2023) RA	Psychological skill training comprises positive psychology, mindfulness, and emotions to enhance the quality of life among athletes.	Theme 6

Note: ED-Experimental Design, OA-Original Article, RA-Review Article, CO-Current Opinion, SR-Systematic Review, PLCT-Prospective Longitudinal Cohort Trial, P-Perspective, CC-Clinical Commentary.

Discussion of Major Themes Focusing on the Lactate Threshold (LT) Training to Enhance Long Distance Running Performance

Theme 1: The Physiology of Lactate Threshold (LT) Training:

LT is defined as the exercise intensity at which there is an exponential increase in blood lactate concentration (Messonnier et al., 2013). This increase in blood lactate has traditionally been associated with the onset of fatigue during prolonged exercise, leading to a decline in performance (Ferraz et al., 2022; Goodwin et al., 2007). However, recent research suggests that LT training may increase the capacity of muscles to produce and use lactate as an alternative energy source, thereby delaying the onset of fatigue and improving endurance performance (Theofilidis et al., 2018). LT training involves training for an extended period of time, typically between 30 minutes and 2 hours, at an intensity slightly above the lactate threshold (Farrell et al., 2021). By training at this intensity, athletes can produce physiological adaptations such as increased lactate clearance, improved mitochondrial function and increased oxidative capacity (MacInnis and Gibala., 2017). These adaptations ultimately lead to improved endurance performance by allowing athletes to sustain higher intensities for longer periods of time without experiencing excessive fatigue (Hughes et al., 2018). Therefore, understanding the physiology of LT training is critical for athletes and coaches who want to optimize their training programs and increase their performance.

Theme 2: Individualization of LT Training Programs

Although LT training is widely recognized as a powerful tool for increasing endurance performance in athletes, a one-size-fits-all approach to such training may not realize the full potential of every athlete and must be tailored to the individual athlete with due consideration of the physiological, psychological and performance-related benefits of personalized approaches. (i) Physiological variability: A recent study highlights the significant variation in the metabolic profiles of athletes, which impacts how they respond to LT training (Nuuttila et al., 2022). Athletes with different metabolic characteristics in particular can benefit from different training strategies. The typology of an athlete is underpinned by the composition of muscle fiber types. Fast-twitch fibers are predominantly found in elite sprinters, while slow-twitch fibers are relatively common in elite endurance athletes. Muscle fatigue in humans depends on the composition of the muscle fiber type. Therefore, an athlete's muscle typology is a crucial influencing factor on performance in several sports activities (Lievens et al., 2020). Therefore, training tailored to these differences can optimize performance. (ii) Psychological considerations include: Personalized training programs tailored to an athlete's preferences and motivations improve adherence and long-term success (Foster et al., 2017). A clear understanding of an athlete's psychological profile can serve as the basis for training recommendations. In addition, LT training should be tailored to an athlete's psychological stress, such as competitive anxiety or self-doubt, and can improve mental resilience and performance (Hamlin et al., 2019). Finally, tailored LT training programs can better mimic the demands of an athlete's target race distance, thereby optimizing race day performance (Casado et al., 2023).

Theme 3: Impact of LT Training Protocol on Endurance Performance

Lactate threshold training has profound and diverse effects on the endurance performance of long-distance runners. Several studies have been conducted to determine the influence of LT training protocols on endurance performance in distance runners, considering its physiological, performance and practical dimensions. Physiological adaptations include metabolic efficiency, whereby LT training induces metabolic adaptations, optimizes the body's oxygen utilization and increases energy production from aerobic pathways (Furrer et al., 2023). Secondly, lactate clearance, where athletes undergoing LT training have an improved lactate clearance rate, delaying the onset of fatigue during prolonged efforts (Nuuttila et al., 2022). A recent study has shown that LT training also impacts performance outcomes by increasing time to exhaustion at submaximal intensities and allowing athletes to endure higher workloads (Foster et al., 2017), thereby improving athletic performance is improved across different disciplines and distances (Casado). et al., 2023). From a practical perspective, tailoring LT training programs to individual lactate thresholds and performance goals increases training effectiveness (Stone et al., 2022), and real-time monitoring of lactate levels and performance metrics using wearable technology and apps provides valuable insights for optimizing LT training (Carrier et al., 2023).

Theme 4: Practical Application of LT Training for Long-Distance Runners

Studies have examined the practical applications of LT training for distance runners, with particular emphasis on training methods, pacing strategies, and practice considerations. Training methods focus on two specific elements viz. First, the implementation of structured training such as tempo runs and threshold intervals, which are essential for addressing and improving lactate threshold (Casado et al., 2022). Second, the emphasis on progressive overload, which consists of gradually increasing the intensity and volume of LT training, allows for sustained adaptations without overtraining (Foster et al., 2017). Likewise, pacing strategies focus on two key aspects viz. (i) Race pace, where training at or slightly above race pace during LT sessions helps runners acclimate to the intensity, they will face on race day (Mumux Mirani., 2022; Bossi et al., 2017); (ii) Practicing negative splitting in LT training runs teaches runners to finish races strong by maintaining a consistent pace and then accelerating (Casado et al., 2023). Finally, practical applications of LT training should be applied considering the real-world scenario with special consideration of terrain and altitude, whereby adapting LT training to different terrain and altitude mimics race conditions and prepares runners for different challenges (Carrier et al., 2023). Likewise, proper fueling and hydration strategies are an essential part of successful LT training and race day performance (Stone et al., 2022).

Theme 5: Monitoring Progress and Adjusting LT Training

Effective LT training requires continuous monitoring of progress and the ability to adjust training protocols as needed, taking into account physiological markers, performance indicators, and real-world considerations. Physiological markers include regular lactate threshold testing such as lactate profiling, which allows athletes to determine their individual thresholds and track changes over time (Nuuttila et al., 2022), and heart rate variability (HRV) monitoring provides insights into an athlete's readiness to train and can indicate overtraining or undertraining (Foster et al., 2017). Performance indicator monitoring is all about tracking race performance results and comparing them to training progress. This helps athletes assess the effectiveness of their LT training (Casado et al., 2023) and estimate time to exhaustion to determine how long an athlete can sustain efforts close to LT during training sessions. This is a valuable indicator of progress (Foster et al., 2017). Finally, the influence of environmental factors such as temperature and altitude on LT training progress must be monitored and training adjusted if necessary (Carrier et al 2023). Additionally, regular nutritional assessments and adjustments must be made to support training adaptations (Stone et al., 2022).

Theme 6: Potential Drawbacks and Mitigation Strategies

There are several drawbacks of LT training on long-distance running performance. First, long-distance runners who engage in lactate threshold training are at risk of overtraining, which occurs when they push their bodies to the edge of their lactate threshold. This type of training can be physically and mentally demanding and can increase the risk of injury. Overtraining

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is characterized by excessive training volume or intensity, resulting in reduced performance, mood disturbances, and physiological imbalances (Foster et al., 2017). Early warning signs of overtraining, including persistent fatigue, sleep disturbances, and mood swings, are critical for prevention (Foster et al., 2017). To mitigate overtraining, one of the strategies is periodization, which involves the systematic planning and organization of training to allow for proper recovery and adaptation (Mukhopadhyay., 2022; Lorenz et al., 2010). By dividing the training program into specific phases, such as base, build, and peak phases, athletes can strategically increase the intensity and volume of their training and at the same time incorporate rest and recovery periods (Lorenz and Morrison, 2015). Additionally, cross-training with different types of exercise limits fatigue and prevents overuse syndrome (Yang, 2019).

Second, overtraining and repetitive nature of LT training can lead to muscle imbalances and an increased risk of overuse injuries in runners (Nuuttila et al., 2022). The constant strain on muscles, joints and connective tissue can lead to overuse injuries such as stress fractures, tendonitis and muscle strains (van der Worp et al., 2015). By conducting biomechanical examinations, those problems that contribute to the risk of injury can be identified (Stone et al., 2022). Additionally, overtraining can lead to decreased immune function, hormonal imbalances, and fatigue, further increasing the risk of injury. (Kreher & Schwartz., 2012). To mitigate these risks, it is important for runners to incorporate rest and recovery days into their training plans, eat a balanced and nutritious diet, stay hydrated, and get enough sleep. These factors play a crucial role in preventing overtraining and injury (Doherty et al, 2021). Third, long-distance runners who engage in lactate threshold training may experience a performance plateau where further improvement is limited or impossible. Several factors can contribute to performance plateaus, including overtraining, inadequate recovery, or genetic limitations (Armstrong et al., 2022). Therefore, it is recommended to carefully manage training load, monitor recovery strategies, and use periodization techniques to challenge the body and continually stimulate further adaptation (Lorenz and Morrison, 2015). Additionally, adding variety to training methods, such as high-intensity interval training or strength and conditioning exercises, also help overcome performance plateaus by targeting different physiological systems and promoting overall fitness improvements (Atakan et al, 2021). Furthermore, it is also emphasized that focusing exclusively on lactate threshold training may neglect the development of the aerobic base, which is crucial for long-distance running (Casado et al., 2023). Studies have therefore recommended incorporating balanced aerobic training, such as long, slow distance running, to build a solid foundation and periodizing the training plan to include different phases of intensity and volume (Casado et al, 2022). Finally, depressed mood, central fatigue and burnout are considered major disadvantages of LT training, which arise from constant training at or near the lactate threshold (Kreher & Schwartz, 2012). To overcome this, athletes use a variety of workouts in the training schedule, including intervals, tempo runs, and easy recovery days, which help break up the monotony and keep the workout routine interesting (Zhang et al., 2023). Additionally, incorporating other strategies such as visualization and mindfulness, as well as positive self-talk, helps athletes improve their concentration, reduce stress, and maintain a positive mindset (Park & Jeon, 2023).

Theme 7: The Role of Nutrition and Recovery in LT Training

Multiple lines of evidence supporting the synergy between LT training, nutrition and recovery highlight the role of nutrition and recovery strategies in maximizing the benefits of LT training for runners (Moisey et al., 2022). Nutritional strategies to maximize the benefits of LT training for runners include carbohydrate periodization, protein intake, and hydration. Carbohydrates are the primary energy source for endurance activities and the implementation of carbohydrate periodization, as described by Impey et al. (2018), in which carbohydrate intake is strategically manipulated to optimize training adaptations. Consuming carbohydrates before and during LT training can improve endurance performance. Likewise, protein is essential for muscle repair and adaptation, and adequate protein intake, as suggested by Phillips and Van Loon (2011), supports recovery and muscle protein synthesis after LT training sessions and allows for faster adaptations. Finally, it is important to drink enough fluids before, during and after training. This is crucial for maintaining performance and preventing heat-related problems during exercise (Sawka et al., 2007).

Recovery practices used to maximize the benefits of LT training for runners include getting a good quality sleep, incorporating active recovery sessions, and regularly practicing stretching and foam rolling exercises. Good sleep is paramount for recovery and adaptation. Sleep duration and quality significantly impact performance, as Fullagar et al. emphasized. (2015). Athletes should prioritize sleep to optimize the benefits of LT training. Incorporating active recovery sessions promotes blood flow and helps eliminate metabolic by-products, potentially reducing muscle soreness and fatigue (Ortiz et al., 2018). Regularly practicing stretching and foam rolling exercises as recommended by Macdonald et al. (2013), can improve flexibility and relieve muscle tension, facilitating recovery between LT training sessions.

Theme 8: Role of Artificial Intelligence in LT training

AI systems are capable of analyzing a variety of data, such as physiological parameters, recovery trends, and past performance data of athletes during LT training (Chidambaram et al., 2022). This allows AI technology to analyze historical performance data and predict an athlete's future performance. Based on this, AI can help athletes set reasonable goals and develop training plans to achieve those goals by understanding the relationship between an athlete's lactate threshold and their racing performance (Pickering and Kiely, 2019).

It is noteworthy that machine learning (ML) models create personalized training plans based on a person's strengths, weaknesses, and goals (Dijkhuis et al., 2018). Such ML models can adjust training based on progress, helping long-distance athletes who struggle with fixed schedules (Furrer et al., 2023). This personalized approach is critical for remote athletes who may not have access to coaches for frequent assessments. By understanding an athlete's lactate threshold and its relationship to race performance, AI can help athletes set realistic goals and create training plans to achieve those goals. Additionally, ML algorithms can analyze biomechanical data to identify injury risk patterns. Athletes can receive training/form modification and risk reduction recommendations to improve their running careers (Rahlf et al., 2022).

Another innovative addition is wearable devices and sensors that can continuously monitor an athlete's physiological data, including heart rate, pace, and lactate levels (Seshadri et al., 2019).

Using AI algorithms, this real-time data can be processed to provide the athlete with immediate feedback. This feedback helps the athlete to spontaneously adjust their training intensity and duration, resulting in more effective training (Hammes et al., 2022). Thus, AI and ML can revolutionize lactate threshold training for distance athletes by providing personalized, data-driven approaches to performance optimization. (Bodemer, 2023).

Theme 9: Future Directions in LT Training Research.

Future directions in LT training research with a focus on innovative methodologies, new technologies, personalized approaches, and integration of genetic insights that will pave the way for the future of athletic performance. Innovative methods include multi-omics analysis, which integrates genomics, proteomics and metabolomics and could provide a comprehensive understanding of individualized LT responses (Bouchard et al., 2011). Furthermore, future research could focus on neurobiological insights to examine the role of the central nervous system in LT adaptation, which could open opportunities for targeted training interventions (Amann., 2011). Research into new technologies includes the invention of advanced wearable sensors that can monitor lactate levels in real time during exercise sessions and could revolutionize LT training (Van Hoovels et al., 2021). Additionally, virtual reality (VR) enhanced LT training environments can provide new opportunities to stimulate and challenge athletes (Andria Shimi et al., 2022). Future research could focus on integrating nutritional genomics to create tailored nutritional plans that support LT adjustments (Guest et al., 2019).

Future research could focus on integrating nutritional genomics to create tailored nutritional plans that support LT adaptations (Guest et al., 2019). Research could also focus on integrating genetic insights such as genetic profiling, which identifies genetic markers associated with LT training responses to support personalized training strategies (Ahmetov and Rogozkin., 2009). Furthermore, epigenetic research is needed to examine epigenetic modifications that influence LT adaptations and responses to training (McGee & Walder, 2018).

Additionally, research could focus on comparing the results of personalized, AI-generated training plans with traditional, non-personalized approaches and identifying factors that influence the effectiveness of AI-driven training plans, such as age, gender, and training history (Casado et al., 2023; Urtats Etxegarai et al., 2021). Finally, there is a need to explore how additional biometric data such as genetic information, sleep patterns, and nutritional data can be integrated into AI algorithms to improve the accuracy and individualization of lactate threshold training programs (Pickering & Kiely, 2019).

Limitations

It is crucial to acknowledge the limitations of using the narrative synthesis approach in this study. Efforts to conduct a comprehensive search of electronic databases such as PubMed and Google Scholar may still miss relevant studies due to variations in indexing, availability of full-text articles, or inclusion criteria used. Subjectivity in identifying and categorizing themes in literature reviews can lead to bias. Efforts were made to minimize bias by involving multiple reviewers, but individual interpretations may have influenced the results. Finally, limiting the study to English-language articles may have led to the exclusion of relevant non-English language publications, which would have reduced the scope and generalizability of the results.

Conclusions

The narrative review reveals the critical aspects of LT protocol training and its impact on distance running performance. When describing the effects of the LT protocol on distance running performance, nine themes emerged in this review. These include the physiology of lactate threshold training (LT), the individualization of LT training programs, the effects of the LT training protocol on endurance performance, the practical application of LT training for distance runners, progression and adaptation to LT training, and potential disadvantages and mitigation strategies, the role of nutrition and recovery in LT training, the role of Artificial Intelligence in LT training and future directions in LT training research.

It is concluded that the Lactate Threshold (LT) protocol plays a central role in the training and performance optimization of endurance athletes. Furthermore, it is emphasized that LT training should be tailored to the individual athlete with due consideration of the physiological, psychological and performance benefits of personalized approaches. When providing LT training, special emphasis should be placed on the training methods, pacing strategies and real-world considerations to train athletes on different terrains and altitudes that mimic racing conditions and prepare runners for different challenges. Likewise, LT training requires continuous monitoring of progress using physiological markers such as regular lactate threshold testing and heart rate variability, as well as monitoring and tracking race performance results and comparing them to study training progress. Further, regular nutritional assessments and adjustments must be made to support training adaptations. This study also pointed out the two main disadvantages of LT training, namely overtraining syndrome (OTS) and the repetitive nature of LT training, which can lead to muscle imbalances. Furthermore, it is emphasized that appropriate nutritional strategies must be employed to maximize the benefits of LT training for runners, including carbohydrate periodization, protein intake, and adequate hydration before, during, and after exercise. This study also suggested that recovery exercises can be used to maximize the benefits of LT training for runners, such as good sleep quality, incorporating active recovery sessions, and regularly practicing stretching and foam rolling exercises. Additionally, the authors emphasized that AI systems analyze physiological and performance data to create personalized LT training plans for distance athletes. Wearable devices and sensors monitor the data and AI algorithms process it to provide instant feedback, leading to effective training and personalized performance optimization. Finally, the authors have outlined some future directions for LT training research, focusing on innovative methodologies, new technologies including virtual reality (VR)-assisted LT training environments, personalized approaches, and integration of genetic insights, paving the way for LT training research.

Conflict of interest

The authors declare that there is no conflict of interest

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