



# NEWER PERSPECTIVES IN LACTATE THRESHOLD ESTIMATION FOR ENDURANCE SPORTS — A MINI-REVIEW

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**Abstract** Lactate threshold (LT) estimation in endurance sports continues to be a widely controversial field amongst sports scientists and students despite beyond 50 years of research. With the advent of technology and superior sensors, LT research has ventured into newer fields involving wearables and artificial intelligence. Still, there is a felt need to understand the focused areas of LT research and to guide the students, sports scientists and coaches. The main aim of this mini-review is to identify research categories in a descriptive manner and to synthesize broad themes for future research from latest literature. A comprehensive electronic search in three databases was performed including only original free full text research articles conducted in athletes and healthy subjects, published in English between 2016 and 2020 following PRISMA guidelines. Out of screened 466 articles, 14 articles were finally shortlisted as per inclusion criteria and the findings were summarized. Five research categories were identified and reviewed. To conclude, there is a need for consensus in Graded Exercise test protocols used, LT concepts validity

for specific sports and the application of valid, reliable noninvasive LT estimation methods in endurance sports. Synthesized broad themes would help guide sports scientists, students and researchers for future research.

**Key words** anaerobic threshold, physical endurance, athletic performance, exercise testing, lactate threshold

## Introduction

In 1808, Jons Jakob Berzelius described lactate for the first time in muscles of hunted stags and postulated the relation between lactate concentration and exercise performed (Kompanje, Jansen, van der Hoven, Bakker, 2007; Needham, Carnis, 1971). Lactate research has evolved since then and has played a prominent role in understanding the bioenergetics during endurance exercise and sporting activities (Brooks, 2018; Gladden, 2008). The blood lactate curve, which is the proportional increase in the blood lactate concentration when plotted against the incremental work rate or time of the activity performed, illustrates the lactate kinetics during graded exercise (Beneke, Leithäuser, Ochentel, 2011; Hall, Rajasekaran, Thomsen, Peterson, 2016).

The understanding of the underlying mechanisms has also evolved over the years with the advent of medical science. The hypothesized concept had begun with muscle anoxia as a cause for increasing lactate through lactate shuttle and use of lactate as an alternative fuel to lactate accumulation due to inability of the physiological mechanisms to clear the formed lactate from the active muscle and hence the lactate accumulation in the blood (Brooks, 2000; Poole, Rossiter, Brooks, Gladden, 2021). This disproportionate rise in blood lactate was called various names like lactate threshold (LT), aerobic threshold, anaerobic threshold, ventilatory threshold etc. in literature. This has been researched widely in endurance sports and is of immense value in training evaluation, prescription and performance prediction (Faude, Kindermann, Meyer, 2009). According to the Kindermann model, the blood lactate curve has been divided into three different phases (Meyer, Lucia, Earnest, Kindermann, 2005). The first rise of lactate above baseline is known as Aerobic threshold or  $LT_1/LT_{AER}$ . Maximum Lactate Steady state (MLSS) is the highest constant work rate during which the lactate remains steady not more than 1 mmol/l than previous level and a second disproportionate rise compared to the work rate is called the Anaerobic threshold or  $LT_2/LT_{ANER}$ . (Faude et al., 2009; Meyer et al., 2005)

LT has been controversial not only with the terminologies used but also with multiple proposed methods given its complex variability (Faude et al., 2009; Hall et al., 2016). Blood lactate curve inherently is determined by various physiological factors like age, gender, type of sports, training level of athletes, sleep, glycogen stores, muscle fibre composition, metabolic enzyme activity, capillary density and mitochondrial density (McArdle, Katch, Katch, 2017). In addition, extrinsic factors like measurement methods used; incremental testing protocols including mode of testing, stage duration and length of the test have also added more complexity to LT estimation (Faude et al., 2009; Foxdal, Sjödin, Sjödin, Ostman, 1994; Jamnick, Botella, Pyne, Bishop, 2018). Several described multiple terminologies and LT concepts have created further confusion among researchers and sports scientists over the years. In a review done by Faude et al. (2009), around 29 LT concepts have been identified (Faude et al., 2009).

Despite the controversies and influence of multiple determinants, estimation of LT in endurance sports has been considered one of the important parameters in sports training and high performance sports owing to its immense value and application. During the early days of research, the LT estimation was considered as a point where the individuals physiological system failure commenced hypothesized as either due to lack of oxygen or

due to reduced lactate clearance. However, lately LT estimation is considered as a point where the individual's physiological system integrates and responds to the stress of the exercise (Poole et al., 2020). Interpretation of the LT estimation provides valuable feedback on the metabolic adaptations that occur with sports training, an important input to the coaches (Kraemer, Fleck, Deschenes, 2011). The estimation of the LT point where the aerobic anaerobic transition happens in endurance sports is nowadays considered a more decisive parameter more than maximal oxygen consumption ( $VO_{2max}$ ) when assessing performance in elite competitive as well as recreational runners (Baron et al., 2008; Etxegarai, Portillo, Irazusta, Arriandiaga, Cabanes, 2018; Meyer, Gabriel, Auracher, Scharhag, Kindermann, 2003). This is generally attributed to the fact that in highly trained endurance athletes, peripheral adaptive changes to training result in improvement in LT percent of  $VO_{2max}$  as compared to  $VO_{2max}$  per se that may become static with training after a certain level in these athletes (McArdle et al., 2017). Approximating the LT point with work rate or speed as well as with time, provides an input to prescribe training intensity to the athlete in an easily understandable and measurable parameter to help improve performance. Assessed individually using other than fixed lactate level LT concepts provides an Individual Anaerobic Threshold (IAT) which generally is used as a benchmark parameter with progression of the training cycle when evaluated longitudinally (Meyer et al., 2000; Poole et al., 2020). The estimation of  $LT_{AER}$  and  $LT_{ANER}$  have been used widely in prescription of training intensity and to periodize the training microcycle by appropriate load monitoring. LT has been prescribed as ranges of percent of  $VO_{2max}$ , Heart rate reserve (HRR), maximum heart rate (MHR) or rating of perceived exertion (RPE) for practical application of the LT zones in training by coaches and athletes (Etxegarai et al., 2018; Pallarés, Morán-Navarro, Ortega, Fernández-Elías, Mora-Rodriguez, 2016).

However, certain practical difficulties still exist in LT estimation and pose a challenge to the sports scientists and the coaches. Measurement of blood lactate involves an invasive sample collection technique, which is by far the most difficult challenge that generally inhibits athletes to participate whole-heartedly in the evaluation (Onor et al., 2017; Sun, Yi, Li, Li, 2017). Moreover, the sophisticated equipment required for the LT estimation is costly and conduct of the test requires expertise. In addition, with multiple LT concepts and the lack of a standard graded exercise testing (GXT) protocol poses further operational constraints (Faude et al., 2009; Jamnick et al., 2018; Pallarés et al., 2016). In the last few years, with technological advances in lactate analyzers using capillary blood and biomedical sensors with micro-electromechanical systems, the LT estimation research is now focused to develop noninvasive, valid and reliable methods for performance prediction (Amann, Subudhi, Foster, 2006; Bunc, Heller, 1989; Cambri et al., 2016; Candotti et al., 2008; Etxegarai et al., 2018; Onor et al., 2017). There is a felt need to update the sports scientists, researchers, coaches and athletes on the latest area of research in LT concepts and update on the validity and reliability of the commonly used LT concepts in various endurance sports. The main aim of this systematic mini-review is to synthesize latest focus areas in LT concepts research and identify broad research themes for future research studies in endurance sports performance.

## Methods

Computerized literature searches following the Preferred Reporting of Items for Systematic Review and Meta-Analyses (PRISMA) guidelines were performed (Moher, Liberati, Tetzlaff, Altman, PRISMA Group, 2009). Search strategy included original research articles only since that was the aim of the study. Free full text articles in English language published between 2016 and 2020 were searched in three scientific databases namely PubMed, Science Direct and Google Scholar. The following keywords were used – 'Lactate threshold', 'Anaerobic threshold', 'sports',

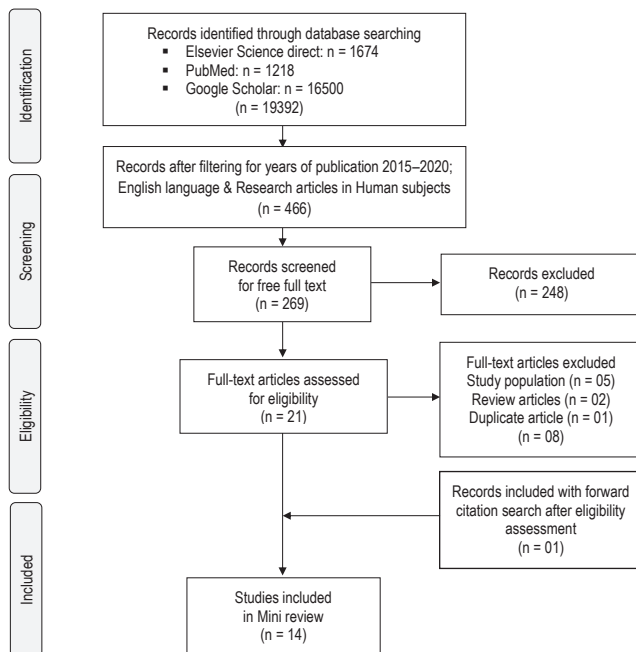
'athletes'. The bibliographies of all located articles were screened and a forward citation search was performed. The search was completed on 20 Nov 2020. Ethical approval was not obtained, as the study essentially was a review of previously published literature.

## Study Eligibility

The study eligibility criteria after screening included the following – Free full text, English language, original research article and healthy or actively sporting study population. The exclusion criteria were any type of review articles, systematic reviews and meta-analyses, conference papers, thesis/dissertation works, letters to editors, unpublished data, book chapters and duplicate publications from search databases. Studies not adhering to the inclusion criteria were excluded after assessment for eligibility. Two reviewers did this independently and in case of a difference of opinion, a third reviewer opined on the same.

## Data Extraction and Synthesis

A single reviewer did the initial article identification and screening from all three search databases. Two reviewers did screening of 21 free full text articles for study eligibility using the predetermined eligibility criteria. Out of the screened articles, both the reviewers independently without any difference in opinion excluded 07 as per exclusion criteria. Finally, 14 research articles published between 2016 and 2020 were included in this Mini-review. Figure 1 shows the method of study selection as per PRISMA guidelines (Moher et al., 2009). Descriptive summary of the extracted data from these articles were explained with the help of tables and graph.

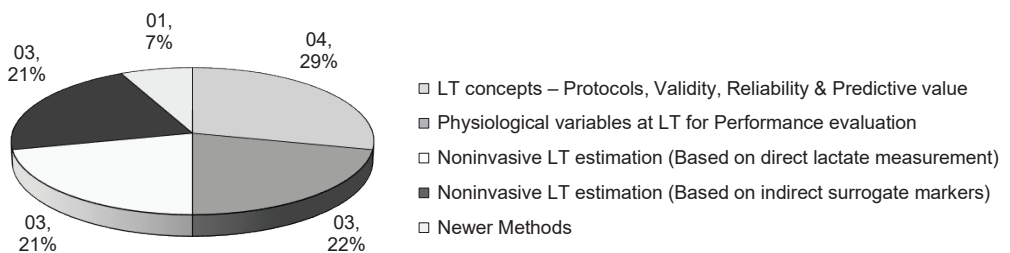


**Figure 1.** Study Selection as per PRISMA Guidelines

Source: Moher et al. (2009).

## Results

Two reviewers thoroughly reviewed all fourteen included research articles. The main purpose of the study being to identify key research areas in LT estimation, resulted in classifying the research areas based on the extracted information from the articles into five broad categories. These broad categories of research area and distribution of number articles among these categories are depicted graphically in Figure 2. Analysis of the country of publication of the articles showed that more than 50% i.e. 08 out of 14 research studies were conducted in Europe. With respect to the study design, we observed 11 cross sectional, 01 post analysis of a Randomized control trial, 01 case report and 01 randomized repeated measure design. Summary of Aim and Key findings of the included research articles grouped under the identified broad research categories is as per Table 1.



**Figure 2.** Research Categories: LT estimation in Sports derived based on the included research articles from 2016 to 2020 shown as actual number of articles under each category and percentage out of total included articles (n = 14)

The two main confusing and controversial areas of LT research namely LT concepts to be employed and Graded Exercise testing protocols (GXT) to be used were extracted from the included research articles and hence has been tabulated in Table 2. Moreover, the study also aimed at recommending future research themes deriving from the latest broader concepts including the sports type and athletes' type that were studied and hence these findings are tabulated in Table 3 separately.

With respect to LT concepts, we identified as many as 25 LT concepts from these last 5 years of original research after excluding the duplication of concepts. These 25 LT concepts include 22 direct LT concepts with 04 newly studied LT concepts. Three LT concepts were indirect methods to estimate LT using surrogate markers namely Heart rate inflection point (HR\_LT), Ventilatory gas Thresholds (VT<sub>1</sub> & VT<sub>2</sub>) and Electromyogram (EMG<sub>th1</sub> & EMG<sub>th2</sub>) thresholds. GXT protocols used in these articles have been extracted and synthesized in a structured format namely mode, stage, rest interval, load increment and blood lactate (BLa) sampling technique used for easy comprehension. None of the GXT protocols used in these 14 research articles was similar as shown in Table 2.

In 12 studies out of 14, either competitive or recreational athletes were the study subjects. The sports studied were running (n = 05, 35.7%), cycling (n = 03, 21.4%), swimming (n = 1, 7.1%), ice skating (n = 01, 7.1%), wheelchair basketball players (n = 01, 7.1%) and multiple sports including track & field athletes, basketball and football (n = 01, 7.1%). Two studies included healthy active subjects (Table 3).

Table 1. Details of Research areas derived from the included articles from 2016 to 2020

S. No.	Research areas derived	Study	Year of study	Country where research was done	Study Design/Study Population	Aim	Main Findings
1	Lactate Threshold (LT) concepts – Protocols, Validity, Reliability & Predictive value of Endurance performance	Fernandes et al.	2016	Brazil	Exploratory laboratory cross sectional study/ 27 Male runners of different training level	To evaluate different LT methods and to determine most reliable LT method of conditioning and training program	Differences in LT methods between Low and Highly trained endurance runners Onset of Blood lactate Accumulation (OBLA <sub>4mmol/L</sub> ) method underestimated LT in Low trained groups
		Pallares et al.	2016	Spain	Cross Sectional Study/ 14 Male well trained cyclists	To assess the validity and reliability of critical workloads found using various LT methods with Ventilatory threshold (VT)	D <sub>max</sub> method was not reliable, even though it coincided well with VT <sub>2</sub> and OBLA <sub>4mmol/L</sub> Both Reliable and Valid LT methods were LT + 2.0 mmol/L and OBLA <sub>4mmol/L</sub> coincided with Maximum Lactate Steady State (MLSS) workload Deduction of Heart Rate reserve (HRR) / Maximum Heart rate (HR <sub>max</sub> ) / rating of Perceived exertion (RPE) based training zones based on the LT (VT <sub>1</sub> ), LT + 0.5 (MLSS) and LT + 2.0 (VT <sub>2</sub> )
		Heuberger et al.	2018	Netherlands	BLC used from a Randomized Placebo controlled single blinded single centre RCT study/ 48 male cyclists	To compare various LT concepts for their repeatability and predictability of endurance performance	Mod D <sub>max</sub> was the best LT concept with both predictive and repeatability
		Jamnick et al.	2018	Australia	Cross sectional study/ 17 Male cyclists	To determine the validity of the lactate threshold (LT) and maximal oxygen uptake (VO <sub>2peak</sub> ) determined during graded exercise test (GXT) of different durations using different LT calculations	(a) D <sub>max</sub> Minimum Lactate equivalent (LaI/Power) + 1.5 mmol/L (LT <sub>3</sub> ) and OBLA <sub>4mmol/L</sub> also performed well. (b) The closest to LT – MLSS values were Modified D <sub>max</sub> method – Exponential Mod D <sub>max</sub> , Log-log Modified LT methods. (c) The closest to LT MLSS was Log – Poly Mod D <sub>max</sub> of GXT4 (d) GXT protocol need to be customized based on the outcome parameter namely VO <sub>2max</sub> or LT as stage duration designed may influence both. Initial speed as well as increment load need to be formulated individually based on predicted VO <sub>2max</sub> rather than Fixed load protocols. (e) Verification Exhaustion bout may not be useful in identifying the VO <sub>2peak</sub> if the GXT duration is longer. Ideal duration of GXT for VO <sub>2max</sub> estimation is 8 – 12 min

1	2	3	4	5	6	7	8
2	Physiological variables at LT Performance evaluation	Pelarigo et al.	2016	Brazil	Cross sectional study/ 10 Elite Female Middle & Long distance competitive Swimmers	To examine the relationship between bioenergetics variables and biomechanical variables while swimming at various intensities (97.5%, 100% and 102.5%)	In all the three testing MLSS intensities, Bioenergetics variable namely Oxygen uptake, Energy cost (C) and Energy Expenditure except HR were constant throughout the test timings. Bioenergetics variables did not change as a function of time. However, Biomechanical factors namely Stroke Rate increased and Stroke length decreased with increasing MLSS intensities. At 102.5% MLSS, although $\dot{V}O_2$ and C were constant, VE and HR increased with time resulting in reduced Oxygen efficiency, increased VE and Blood Lactate would be a reason for early fatigue and non-completion of full 30 min swim by subjects
		Scheer et al.	2019	Germany	Cross sectional study/ 25 male trail runners	To examine established LT concepts in Trail running and evaluating in two different distances for performance prediction	(a) LT correlated with race performance in short trail running (21km –XXS format) (b) LT predicted performance in slower runners compared to faster runners. (c) $OBLA_{normal}$ predicted better than IAT in these runners.
		Otto et al.	2019	Germany	Randomized repeated measure design/ 08 competitive wheelchair basketball players	To compare arm crank ergometer with treadmill wheelchair propulsion ergometer using physiological parameters at peak performance and Individual Anaerobic threshold (IAT) to provide with optimal training prescription recommendations	(a) Treadmill group showed significantly higher $\dot{V}O_2$ , HR, and Energy Expenditure at peak performance as well as at IAT. (b) Blood Lactate values were significantly lower than Arm crank ergometer group (c) OBLA <sub>normal</sub> predicted better than IAT in these runners.
3	Noninvasive LT estimation (Based on direct lactate measurement)	Onor et al.	2017	Italy	Cross sectional Experimental study/ 5 Healthy volunteers (2 males and 3 females)	To validate non-invasive method of measurement of lactate levels in sweat during cycling exercise	(a) Non-invasive Sweat lactate measurement using Screen Printed Carbon Electrodes (SCPE) using potentiometric sensor technology correlated linearly with Sweat samples analysed using High Performance Liquid Chromatography (HPLC)
		Erxegarai et al.	2018	Spain	Cross sectional study/ 143 recreational runners	To create an intelligent machine learning system that is capable of estimating LT in endurance running sports	(a) Machine learning (ML) method used to estimate Lactate curve, thus ML may predict the LT accurately overcoming the problems in blood lactate measurement error that are inherent to LT tests. (b) ML estimated LT correlated well with actual LT measured and running performance in recreational runners.

1	2	3	4	5	6	7	8
		Exegarai et al.	2019	Spain	Experimental study/ 50 Recreational runners	To propose heuristic method as an accessible LT method and integrate in decision making of recreational runners	(a) $D_{max}$ method though more commonly used has individual error due to various reasons. Increasing the number of Lactate points decreases the variability (b) LT is highly dependent on $V_{peak}$ (maximum workload) which is again variable between individuals. So developing method without $V_{peak}$ may reduce the error. (c) Heuristic approach with equation, $LT = 60\%$ of endurance running speed reserve + Initial running speed on treadmill during GXT can predict the LT workload.
4	Noninvasive LT estimation (Based on indirect surrogate markers)	Borges et al.	2016	New Zealand	Cross Sectional study/ 14 adult recreational and highly trained athletes (7 males and 7 females)	To determine the levels of agreement between the Wearable device derived (WLT) and traditional LT methods and the correlation of WLT method with inter & intra device reliability of WLT (Near Infrared Spectroscopy)	(a) WLT method was not significantly different from the traditional LT methods. (b) The correlation of WLT method was high to very high between these methods, with highest being $OBLA_{limult}$ LT method. (c) The error of measurement between WLT method and OBLA LT method was the lowest. (d) Inter-device as well as Intra-device reliability of WLT was high ( $r=0.97$ in both the cases)
		Sun et al.	2017	China	Case report/ 4 healthy volunteers (02 males and 02 females – among them 02 young athletes and 02 adults)	To introduce a novel noninvasive lactate threshold Heart rate prototype as an alternative for invasive LT tests using a T-shirt integrated with ECG electrodes and LT computing algorithm	(a) Noninvasive fabric based indirect method to identify the lactate threshold Heart rate prototype using HR inflection method used by Conconi method (b) Voice command based on the LT-HR achieved to instruct the athlete to adjust the pace to delay fatigue
		Plucco et al.	2020	Canada	Cross sectional study/ 10 well trained ice skaters	To assess the validity of first and second breakpoints in EMG signal from lower limb muscles using visual and mathematical models and compare them with $VT_1$ and $VT_2$ during skating	(a) $EMG_{th2}$ can be identified compared to $EMG_{th1}$ in 80% of the cases using both the methods. (b) $EMG_{th2}$ was not different from $VT_2$ using mathematical model as compared to visual method. (c) 2-level regression fitting of Blood lactate curve yielded better validity of $EMG_{th2}$ than other methods. (d) Among the 6 muscles studied, Knee extensors and hip extensors presented highest $EMG_{th2}$ detection.
5	Newer Concept: Inter Threshold Area (ITA)	Capelá et al.	2018	Spain	Cross sectional study/ 606 male adult athletes and PE students	To examine the Inter threshold area between $VT_1$ and $VT_2$ for individuals with different endurance capacities	(a) ITA values were higher in endurance predominant sports (Cyclists > Football > Track & Field > Artistic Gymnasts) (b) It is not convenient to express $VTs$ as percentage of $VO2max$ . Rather, absolute values of $VTs$ and ITA must be used to compare between individuals.



**Table 2.** LT concepts and Graded Exercise testing (GXT) Protocols employed in the included Research articles

Study	Aim of the study	GXT Methods/ protocol used	LT concept employed (Direct & Indirect)
	2	3	4
Fernandes et al. (2016)	To evaluate different LT methods and to determine most reliable LT method for level of conditioning and training program	<b>GXT Mode:</b> Continuous Treadmill running <b>Stage duration:</b> 4 min <b>Load increment:</b> 1km/h speed every stage with constant 1% grade <b>Blood Lactate (BLa) sampling:</b> Finger tips capillary blood (CPL) without interruption after every stage	<ul style="list-style-type: none"> <li>- Baseline + 1mmol/L,</li> <li>- <math>OBLA_{4mmol/L}</math>,</li> <li>- Semi-log method of blood lactate and intersection of the two linear segments</li> </ul>
Pelargo et al. (2016)	To examine the relationship between bioenergetics variables and biomechanical variables while swimming at various percentage of MLSS intensities (97.5%, 100% and 102.5%)	<b>GXT Mode:</b> Intermittent 25m Indoor Swimming <b>Stage:</b> 200m swim lap <b>Rest:</b> 30s in between 200m lap <b>Load increment:</b> 0.05m/s until voluntary exhaustion <b>BLa Sampling:</b> Ear lobe CPL at rest, during 30 s rest interval between stages and 2 min after voluntary exhaustion	LT: Intersection between a linear and exponential regressions of BLC
Pallarés et al. (2016)	To assess the validity and reliability of critical workloads found using various LT methods with VT	<b>GXT Mode:</b> Ramp protocol Cycle ergometer <b>Stage:</b> 1 min <b>Load increment:</b> 25W/min until exhaustion <b>BLa Sampling:</b> CPL collected every 2 min without interruption	<ul style="list-style-type: none"> <li>- LT defined as the highest workload without rise in Blood lactate above baseline,</li> <li>- LT + 1mmol/L,</li> <li>- LT + 0.5; LT + 1.5; LT + 2.0; LT + 2.5 and LT + 3.0 mmol/L,</li> <li>- <math>D_{max}</math> method – Point on the 3<sup>rd</sup> order polynomial regression curve of Blood lactate that yields the maximum distance from the line joining the two end points of the curve,</li> <li>- <math>OBLA_{4mmol/L}</math></li> </ul>
Borges et al. (2016)	To determine the levels of agreement between the Wearable device derived LT (WLT) and traditional LT methods and the inter & intra device reliability of WLT	<b>GXT Mode:</b> Continuous Treadmill running <b>Stage:</b> 3 min <b>Load increment:</b> Starting with 4.8 km/h and increased to 9.3 – 11.7km/h in 2 <sup>nd</sup> stage and further stage increment by 0.3 to 1.1 km/h until exhaustion. <b>BLa Sampling:</b> Fingertip CPL obtained 10 seconds before the end of every stage and 1 min post exercise during recovery	<ul style="list-style-type: none"> <li>- Linear spline fitting method,</li> <li>- <math>D_{max}</math> method,</li> <li>- Modified <math>D_{max}</math> method,</li> <li>- First rise of blood lactate &gt; 1 mmol/L method,</li> <li>- <math>OBLA_{4mmol/L}</math>,</li> <li>- WLT patented LT estimation algorithm (<b>Indirect</b>)</li> </ul>

1	2	3	4
Sun et al. (2017)	To introduce a novel noninvasive individual lactate threshold Heart rate prototype as an alternative for invasive LT tests using a T-shirt integrated with conductive fabric ECG electrodes and LT HR computing algorithm	<b>GXT Mode:</b> Continuous Treadmill running <b>Stage:</b> Not described <b>Load increment:</b> Initial speed of 16km/h and 15-degree gradient until identification of HR inflection point (LT -HR) or 75% of age predicted Max HR if no inflection happened. With identification of LT- HR, a voice command from the mobile app instructs the individual to adjust the pace to delay onset of fatigue <b>BLA Sampling:</b> Not described	Modified Conconi HR_LT Inflection point (Indirect)
Onoret al. (2017)	To validate non-invasive method of measurement of lactate levels in sweat during cycling exercise	<b>GXT Mode:</b> Continuous Cycle ergometer <b>Stage:</b> 3 min <b>Load increment:</b> Maintaining a cadence of 70 - 75 rpm until 18 min of exercise. <b>Lactate Sampling:</b> Sweat Lactate samples collected at the end of every stage.	Not used. Only validation of sweat lactate with HPLC done.
Etvegarai et al. (2018)	To create an intelligent machine learning system that is capable of estimating LT in endurance running sports.	<b>GXT Mode:</b> Intermittent Treadmill running <b>Stage:</b> 4 min <b>Rest:</b> 1 min <b>Load increment:</b> 1% slope and 9 km/h to start with and increased by 1.5 km/h every 4 min until 13.5 km/h and there after 1 km/h till exhaustion <b>BLA Sampling:</b> Earlobe CPL collected at each stage during 1 min rest phase after each stage.	$D_{max}$ Method with at least 5 lactate sample points during the test
Jammick et al. (2018)	To determine the validity of the lactate threshold (LT) and maximal oxygen uptake ( $\dot{V}O_{2max}$ ) determined during graded exercise test (GXT) of different durations and using different LT calculations	<b>GXT Mode:</b> Customised Cycle ergometer (05 GXTs performed) <b>Stage:</b> 1- min, 3-min , 4-min, 7-min and 10-min in 5 GXTs were tested for suitability for LT estimation followed by a Verification Exhaustion bout after cessation of GXT for estimation of $\dot{V}O_{2peak}$ <b>Load increment:</b> Calculated based on the demographic and Physical activity readiness derived $\dot{V}O_{2max}$ data <b>BLA Sampling:</b> Antecubital venous blood sampling at the end of each stage	<ul style="list-style-type: none"> <li>- Log -log method,</li> <li>- OBLA - 2.0, 2.5, 3.0, 3.5, 4.0 mmol/L,</li> <li>- Baseline + Absolute value - B + 0.5, 1.0, 1.5mmol/L,</li> <li>- Dmax,</li> <li>- Mod Dmax,</li> <li>- Respiratory Compensation point (VT),</li> </ul> Newer LT concepts: <ul style="list-style-type: none"> <li>- Exponential Dmax,</li> <li>- Log-log Modified Dmax,</li> <li>- Log-log Exponential Mod Dmax,</li> <li>- <math>RCP_{MLSS}</math> - Estimated <math>MLSS</math> from regression equation based on RCP from GXT<sub>1</sub></li> </ul>

1	2	3	4
Heuberger et al. (2018)	To compare various LT concepts for their repeatability and predictability of endurance performance	<b>GXT Mode:</b> Continuous Cycle ergometer <b>Stage:</b> 5 min <b>Load increment:</b> initial resistance 75W with increment of 25W/5stage till exhaustion <b>BLA Sampling:</b> Antecubital vein sample between 4:15 min to 4:45 min of each stage	<ul style="list-style-type: none"> <li>- LT1 – Observer determined first rise in BLA,</li> <li>- LT2 – B + 1mmol/L,</li> <li>- LT3 – Minimum Lactate equivalent (La/ Power) + 1.5 mmol/L</li> <li>- LT4 – First BLA value that shows &gt; 1mmol/L between two BLA values,</li> <li>- LT5 – Min Lactate Equivalent (La/VO<sub>2</sub>),</li> <li>- OBLA<sub>4mmol/L</sub>,</li> <li>- D<sub>max</sub>,</li> <li>- Mod D<sub>max</sub></li> </ul>
Scheer et al. (2019)	To examine established LT concepts in Trail running and evaluating in two different Trail distances for performance prediction	<b>GXT Mode:</b> Continuous Step test <b>Stage:</b> 3 min <b>Load increment:</b> Start with 8 km/h and increment of 2km/h every 3 min until exhaustion or task failure <b>BLA Sampling:</b> Ear lobe CPL after each stage and at termination	<ul style="list-style-type: none"> <li>- LT<sub>AER</sub> – Bla &gt; baseline value,</li> <li>- IAT – Bla &gt; 1.5mmol/L above LT<sub>AER</sub>,</li> <li>- OBLA<sub>4mmol/L</sub></li> </ul>
Exegarai et al. (2019)	To propose heuristic method as an accessible LT method and integrate in Training decision making of recreational runners	<b>GXT Mode:</b> Intermittent Treadmill running <b>Stage:</b> 4 min <b>Rest:</b> 1 min <b>Load increment:</b> 1% slope and 9 km/h to start with and increased by 1.5 km/h every 4 min until 13.5 km/h and there after 1 km/h till exhaustion <b>BLA Sampling:</b> Earlobe CPL collected at each stage during 1 min rest phase after each stage	D <sub>max</sub> Method with at least 5 lactate sample points during the test
Otto et al. (2019)	To compare arm crank ergometer with treadmill wheelchair propulsion ergometer using physiological parameters at peak performance and IAT to provide with optimal training prescription recommendations	<b>GXT Mode:</b> Intermittent Arm Crank ergometer Vs Intermittent Treadmill Propulsion <b>Stage:</b> 3 min in both protocols <b>Rest:</b> 30s in both protocols <b>Load increment:</b> Starting 50W and 20W/3min at 60ppm till exhaustion Vs Starting 6kmph/ 1% slope with 1.5kmph increment every 3 min until exhaustion <b>BLA Sampling:</b> Earlobe CPL collected at each stage during 30s min rest phase after each stage	Minimum lactate equivalent + 1.5 mmol/L (Dickhuth LT concept ref)
Plucco et al. (2020)	To assess the validity of first and second breakpoints in EMG signal from 6 different lower limb muscles using visual and mathematical models and compare them with VT1 and VT2 during skating	<b>GXT Mode:</b> Continuous Skating test on a slide board of polyethylene surface <b>Stage:</b> 3 min <b>Load increment:</b> Starting with 30 push offs per minute (ppm) and increased by 3 ppm every stage until exhaustion <b>Sampling:</b> Breath to breath metabolic analyser for expired gases was done	VT <sub>1</sub> and VT <sub>2</sub> by visually detected by Ventilatory Equivalent method (VE/VO <sub>2</sub> and VE/VCO <sub>2</sub> ) (Indirect)

**Table 3.** Broad Themes Identified in LT estimation for endurance sports performance for future research

S. No.	Study	Population for which applicable	Sports for which applicable	Research Area derived	Broad Themes identified for future research
1	Fernandes et al. (2016)	Runners	Middle and Long distance Running	Lactate Threshold (LT)	1. Development of LT estimation specific GXT protocol including appropriate stage duration, length of the test, load increment and minimum lactate samples required.
2	Pallarés et al. (2016)	Well Trained Male Cyclists	Cycling	concepts –	2. Validity & Predictive value of LT concepts for competitive endurance sports based on training level and competitive level using common GXT protocols.
3	Heuberger et al. (2018)	Well trained cyclists	Cycling	Protocols, Validity, Reliability &	3. Validation and Reliability testing of Newly developed Modified $D_{max}$ LT method (Log-Poly Modified Dmax method) in both cycling as well as other endurance sports.
4	Jamnick et al. (2018)	Trained Cyclists	Cycling	Predictive value of Endurance performance	4. Identification of Sports-specific valid LT concept and most acceptable LT concept for multiple sports
5	Pelarigo et al. (2016)	Competitive female Swimmers	Middle and Long distance Swimming		1. Comparison of LT estimation based on gender within various endurance sports.
6	Scheer et al. (2019)	Male Trail Runners	Trail running	Physiological variables at LT	2. Correlation of other performance indicators with LT estimation to comprehensively evaluate and predict endurance performance.
7	Otto et al. (2019)	Competitive Wheelchair basketball players	Wheelchair Basketball	Performance evaluation	3. Development of Sports specific LT methods for Paralympic sports
8	Onor et al. (2017)	Active Healthy Adults	Any sports		1. Validation studies of Sweat lactate analysis in endurance athletes against Blood lactate assessment methods.
9	Etxegarai et al. (2018)	Recreational Runners, triathlon and Trail runners	Long distance Running	Noninvasive LT estimation	2. Machine learning models in competitive endurance athletes and validation against gold standards like MLSS and Race performance.
10	Etxegarai et al. (2019)	Recreational runners	Running	(Based on direct lactate measurement)	3. Noninvasive ML models in special populations like military personnel and recruits for performance prediction where expertise and sophisticated equipment is an operational constraint
11	Borges et al. (2016)	Recreational and Highly trained athletes	Running	Noninvasive LT workload estimation	1. Validation of noninvasive LT workload estimation based on indirect surrogate markers in competitive endurance athletes using Gold standard LT tests like MLSS and Race performance.
12	Sun et al. (2017)	Active healthy individuals	Any sports	(Based on indirect surrogate markers – Near Infrared Spectroscopy (NIRS), Heart Rate (HR) and Electromyogram (EMG)	2. Validation and Reliability of HR-LT zone based computing algorithm in exercise prescription among recreational as well as competitive runners using standard methods
13	Piucco et al. (2020)	Well trained long track Speed Skaters	Ice skating		
14	Capellá et al. (2018)	Athletes	Cycling, Running, Swimming, Track & Field, Basketball and Football	Newer Concept: Inter Threshold Area (ITA)	Practical application of ITA using LT methods in various competitive as well as recreational endurance sports in training prescription and performance evaluation

## Discussion

The main findings of this review showed that five broad research categories (Table 1) have emerged over the last 5 years of LT research with the focus of research skewing more towards noninvasive LT estimation using wearables and artificial intelligence (Figure 2). Most of these research studies were conducted in European countries and developed nations signifying the present research trend and highlighting the need of pursuing focused research on LT in sports in other parts of the world. The common sports in which LT research was conducted are running and cycling, contributing more than 50% of the other endurance sports. A recent study employed LT estimation in performance assessment of wheelchair basketball players also, thereby applying the LT concepts in para-athletes too.

Although in the last decade, many review articles on lactate kinetics and LT training were published, it was seen that most of these review articles focused on either the evolving lactate kinetics or LT concepts (Beneke et al., 2011; Galán-Rioja, González-Mohino, Poole, González-Ravé, 2020; Hall et al., 2016; Poole et al., 2021; Rogatzki, Ferguson, Goodwin, Gladden, 2015; Sarma, 2018). Hence, our main aim was to identify broad research categories in recent LT research especially in athletes and healthy individuals over the last 05 years for identification of focused areas and to synthesize broad themes for future research in sports. The eligibility criteria was also designed accordingly.

### GXT Protocol Design

Graded exercise test (GXT) protocols in terms of stage duration, continuous or intermittent between stages, load increment with each stage as well as the method of lactate measurement have been considered as independent variables that influence the LT estimation irrespective of the concepts that are employed. (Bentley, McNaughton, 2003; Bentley et al., 2007; Jamnick et al., 2018). As shown in Table 2, amongst the 14 research studies included, each study has followed a different protocol design. There has been no clear consensus with respect to appropriate use of GXT for LT estimation in terms of all the protocol components (Jamnick et al., 2018). Jamnick et al. (2018) have studied the validity of almost 16 LT concepts in about five different GXTs with respect to the stage duration using customised load increments based on demographic and Physical activity readiness scale scoring (Jamnick et al., 2018). LT estimation varied with all the GXT duration and the closest LT concepts to MLSS were newer modified  $D_{max}$  methods employed in this study namely Exponential  $D_{max}$ , Log-log Modified  $D_{max}$  and Log-log Exponential Mod  $D_{max}$ . Log – Poly Mod  $D_{max}$  of GXT with 4 min stage duration was the closest to  $LT_{MLSS}$ . Moreover, customization of load increment with stages as well as based on the outcome parameters have been recommended by the authors of this study (Jamnick et al., 2018).

### LT concepts – Validity, Reliability and Predictive value

Faude et al. (2009) have carried out a comprehensive review on validity of various LT concepts (Faude et al., 2009). According to this review, validation of the LT concepts was done either with MLSS or competition performance.  $LT_4$  or  $OBLA_{4mmol/L}$  and IAT (Stegmann, Kindermann, Schnabel, 1981) were by far the most commonly studied LT concepts against MLSS for validation in various endurance sports (Faude et al., 2009). As summarized in Table 1 (S. No. 1), we found four research studies conducted with the aim of evaluating validity, repeatability and predictive value of LT concepts (Fernandes et al., 2015; Heuberger, Gal, Stuurman, Keizer, de Muinck, Miranda, Cohen,

2018; Jamnick et al., 2018; Pallarés et al., 2016). Three studies were conducted in cyclists (Heuberger et al., 2018; Jamnick et al., 2018; Pallarés et al., 2016) and one study in runners (Fernandes et al., 2015). To summarize these findings,  $LT_4$  or  $OBLA_{4\text{mmol/L}}$  again fared well in all the studies with respect to validity, repeatability and predictive value. However, use of  $LT_4$  underestimated LT in low-trained athletes (Fernandes et al., 2015). Controversy in  $D_{\text{max}}$  LT concept was observed between these studies (Heuberger et al., 2018; Pallarés et al., 2016). However, Jamnick, Botella, Pyne, Bishop (2018) with newer LT concepts of modified  $D_{\text{max}}$  found them to be closest to  $LT_{\text{MLSS}}$ . Apart from these LT concepts,  $LT + 2.0 \text{ mmol/L}$  and Minimum Lactate equivalent (La/ Power) + 1.5 mmol/L have also been studied in these studies with good validity and predictive value in cyclists (Heuberger et al., 2018; Pallarés et al., 2016).

### Physiological variables at LT for performance evaluation

Under this research area, we could identify three articles as shown in Table 1. All these three studies were done in different endurance sports like swimming, trail running and wheelchair basketball players. Pelarigo, Greco, Denadai, Fernandes, Vilas-Boas, Pendergast (2016) have studied the relationship of bioenergetics variables and biomechanical variables of female swimmers at various percentages of MLSS. They have found that at 100% MLSS, bioenergetics variables were constant but biomechanical variables namely stroke rate increased and stroke length reduced. This study compared biomechanical variables and their relationship with physiological variables at various MLSS intensities for performance evaluation (Pelarigo, Greco, Denadai, Fernandes, Vilas-Boas, Pendergast, 2016). We identified a similar study relating biomechanical variables of running with energy cost or running economy at LT mainly in runners (Joubert, Guerra, Jones, Knowles, Piper, 2020). Scheer, Vieluf, Janssen, Heitkamp (2019) examined established LT concepts in Trail runners of varying distances for the first time and evaluated LT estimation for performance prediction (Scheer et al., 2019). Otto, Reer, Holtfreter, Riepenhof, Schröder (2019) compared arm crank ergometer with treadmill wheelchair propulsion ergometer using physiological parameters at peak performance and IAT to provide optimal training prescription recommendations in wheelchair basketball players (Otto et al., 2019). All these three research studies provide the latest insight into the utilization of LT concepts and physiological variables at LT in performance evaluation and more so importantly application of LT for training prescription even in para-athletes.

### Noninvasive LT estimation (Lactate related)

Because of the major drawback of invasive methodology used for obtaining blood samples, various research studies have focused on noninvasive LT estimation in an attempt to negate this major drawback. The noninvasive LT estimation can be broadly divided into two major research areas as Lactate related i.e. using alternate source of lactate or by using machine learning methods and Indirect i.e. using surrogate markers for lactate itself to identify the LT indirectly. We identified three research studies under this research area. Onor, Gufoni, Lomonaco, Ghimenti, Salvo, Sorrentino, Bramanti (2017) have validated sweat lactate level measurement during cycling exercise with High Performance liquid chromatography in healthy volunteers (Onor et al., 2017). However, LT using sweat lactate method if validated with conventional LT estimation would prove to be of immense value in future LT research. Etxegarai, Portillo, Irazusta, Arriandiaga, Cabanes (2018) from Spain have tried developing machine learning based LT prediction algorithm and validated with blood lactate LT estimation in recreational runners (Etxegarai et al., 2018). In addition, using heuristic approach, the same research group has developed an equation for recreational runners

for LT workload estimation based on running speed reserve and initial running speed on treadmill during a GXT (Etxegarai, Portillo, Irazusta, Koefoed, Kasabov, 2019). These methods if further researched and validated would prove very useful for athletes and active individuals where expertise and facilities for LT estimation are not available.

### Noninvasive LT estimation (Indirect)

This category of research idea included noninvasive LT estimation using surrogate markers that was popular since the years of Wasserman and Conconi using ventilatory thresholds and heart rate inflection as indirect markers of LT (Conconi, Ferrari, Ziglio, Droghetti, Codeca, 1982; Conconi et al., 1996; Wasserman, McIlroy, 1964). In this review, we located three research articles in this area of LT research, one each from New Zealand, China and Canada. Borges, Driller (2016) in their study had evaluated a wearable device based LT estimation (WLT) using the Near Infrared Spectroscopy principle in runners (Borges, Driller, 2016). The device that was worn over the calf, has an algorithm to predict the LT, and was shown to be valid and reliable in this study. The correlation of WLT was highest with  $OBLA_{4\text{mmol/L}}$  and both inter-device as well as intra-device reliability were high ( $r = 0.97$  in both the cases) (Borges, Driller, 2016). Sun, Li, Li (2017) from China had published a case report to introduce a novel noninvasive individual lactate threshold Heart rate prototype as an alternative for invasive LT tests using a T-shirt integrated with conductive fabric ECG electrodes and HR\_LT computing algorithm (Sun et al., 2017). In this study, they had devised an indirect HR\_LT based algorithm to identify the LT training zones using modified Conconi's method of heart rate inflection point using the ECG electrodes. Despite the inherent accuracy issues with heart rate due to various confounding variables, heart rate based exercise & sports training is popular and commonly used in wearable technology. Hence, this noninvasive indirect LT estimation research category still merits focus among researchers. Piucco, Diefenthaler, Prosser, Bini (2020) have assessed the  $EMG_{th1}$  and  $EMG_{th2}$  breakpoints from 6 different lower limb muscle sites with  $VT_1$  and  $VT_2$  in Ice skaters (Piucco et al., 2020). This study though did not directly use LT methods to validate was still included to bring out the importance of noninvasive LT research using indirect surrogate markers even for validation, here  $VT_1$  and  $VT_2$ .

### Newer Methods

A final research category as Newer methods was framed to include research studies that were not fitting into any of the above four categories. Capellá et al. (2018) from Spain had presented a new concept of inter threshold area between  $VT_1$  and  $VT_2$  among individuals with varying endurance capacities (Capellá, Peinado, Moro, Revenga, Esteves, Montero, 2018). Further application of this new concept in training and performance evaluation of athletes are promising research areas for future research.

### Future research themes

One of the objective of this review was also to suggest broad research themes for future research to sports scientists, students, coaches and physical education professionals. Table 3 shows the synthesized broad themes based on the categorized research areas and included original research studies under the respective categories. Despite more than 50+ years of Lactate Research in sports (Poole et al., 2020), consensus in GXT protocol, LT concept for specific sports, validation of common LT sports in endurance sports other than running and cycling, gender difference in LT estimation and LT research in Para-sports, validated noninvasive lactate measurement techniques are lacking. There is certainly immense scope of future research in these broad research themes.

Even though the aim of the review was to identify research categories and provide a roadmap for future research in LT estimation in sports, there were few limitations in terms of the search being restricted to freely available full text articles in the databases. This would have limited the number of research ideas in the field. In addition, since the search was restricted to athletes and healthy active adults, this review lacks research themes done in patient population and clinical research.

## Conclusion

Lactate threshold, despite a long research history, is still an actively researched area globally in sports due to its varied applications. The researchers are focused mainly on GXT study protocols, evaluating validity & predictive value of LT concepts and developing noninvasive methods for LT estimation using wearable technology and machine learning arena for performance enhancement in competitive as well as recreational sports. This review has laid the roadmap for future research themes to guide the sports scientists, students and researchers and future research based upon the suggested themes will shed more light upon the conundrum that is LT research.

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