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Journal of Science & Cycling
Breakthroughs in Cycling & Triathlon Sciences

Review Article

Methodological Approaches in Testing Maximal Lactate Accumulation Rate - νLamax: A Systematic Review

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Received: 6 January 2025 **Accepted:** 6 August 2025 **Published:** 10 September 2025

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Abstract

In 1984 Mader constructed a mathematical model of human energy metabolism to understand the metabolic origin behind the maximal lactate steady state. An integral parameter of Mader's model requires knowledge of the maximal rate of glycolysis, which Mader derived from the maximal lactate formation rate within the muscle cell. However, in-vivo the maximal lactate formation rate within the muscle cannot be measured. Subsequently, Mader proposed the utility of measuring the rate of maximal blood lactate accumulation following supramaximal exercise as an indirect measure of glycolytic flux, termed νLamax. Recently, the νLamax has gained popularity amongst researchers and practitioners as an indirect assessment method to determine the maximal glycolytic rate. Currently, there is a distinct lack of continuity in methodological approaches between researchers. Therefore, the primary aim of this systematic review was to evaluate the current methodological approaches applied to test the νLamax. Based on the findings we make practical recommendations for researchers to adopt to promote standardisation of test procedures. Comprehensive searches of the databases; PubMed, SCOPUS, Google Scholar, and SPOLIT, identified 3545 articles for screening (1984-2024). In total 27 articles were included within this review, with seven different modalities identified. The results from this systematic review highlight several key considerations which need to be considered when testing the νLamax including; alactic timespan, test duration, baseline blood lactate concentration, modality specificity, movement velocity, recovery procedures, and post exercise blood lactate sampling times. Based on these findings this review provides detailed recommendations to standardise νLamax methods considering pre-test, test, and post-test factors.

Keywords

Glycolysis; νLamax; Maximal Lactate Accumulation; Anaerobic Power; Sprint Performance; Blood Lactate.

1 Introduction

The performance of high intensity exercise is largely influenced by the maximal rate of the energy generating pathways to produce contractile force (Heck et al., 2003). A non-invasive identification of each energy system utilisation is widely sought after, as the detection of deficiencies, provide the basis for training recommendations. Direct measurements of the oxidative energy system can be analysed via expired air during exercise (Van Hooren et al., 2024). Whereas a direct measurement of alactic and glycolytic energy capacity/power is challenging due to metabolic substrates located within the muscle cell (Heck et al., 2003). Direct measurements of muscle phosphates require complex and invasive procedures; muscle biopsy (Parolin et al., 1999), and phosphorus magnetic resonance spectroscopy (Wackerhage et al., 1998). Whilst alactic substrate utilisation can be estimated indirectly via post exercise expired air (Knuttgen, 1970) and near infrared spectroscopy (McCully et al., 1994). Currently, there is no non-invasive gold standard to determine glycolytic metabolic power.

Analysis of post exercise capillary blood lactate concentration to determine the maximal rate of blood lactate accumulation (νLa_{max}), has gained traction as an indirect marker of the glycolytic rate. This approach has been applied across various exercise modalities following short-term maximal exercise; cycling (Hauser et al., 2014; Adam et al., 2015; Dunst et al., 2023a; Harnish et al., 2023; Yang et al., 2023; Haase et al., 2024; Langley et al., 2024; Meixner et al., 2024), hand-cycling (Quittmann et al., 2018; Quittmann et al., 2021a), running (Hanon et al., 2011; Wawer et al., 2020; Quittmann et al., 2020; 2021b; 2023), rowing (Held et al., 2023; Schunemann et al., 2023), swimming (Sperlich et al., 2010; Teixeira et al., 2022; Mavroudi et al., 2023), and following isokinetic force tests of maximal strength loads (Nitzsche et al., 2018a; Nitzsche et al., 2020).

The glycolytic power of an athlete is traditionally associated with accelerations and the sprint finish during endurance races (Quittmann et al., 2023). However, the interaction of the maximal glycolytic (νLa_{max}) and oxidative power ($\dot{V}O_{2max}$), have been successfully applied to mathematical simulations of human energy metabolism, to predict the power at maximal lactate steady state (MLSS) (Mader, 1984; Mader and Heck, 1986; Mader, 2003; Hauser et al., 2014; Hommel et al., 2019; Poffé et al., 2024). The gold-standard for determining the MLSS requires multiple constant load trials, which are time consuming, training restrictive, and does not explain the underlying physiological mechanisms (Quittmann et al., 2020). Therefore, approaches applying the metabolic power from the νLa_{max} and $\dot{V}O_{2max}$ to calculate the MLSS provide the metabolic profile of the athlete in a time effective method. Subsequent insight may allow training interventions to be tailored to an individual's metabolic profile by altering either the athletes νLa_{max} or $\dot{V}O_{2max}$ to improve MLSS (Hommel et al., 2019).

1.1 Theoretical Concept of the Maximal Lactate Accumulation Rate (νLa_{max})

Lactate is an intermediate metabolite between glycolysis and mitochondrial respiration. Pyruvate is converted into lactate via the enzyme lactate dehydrogenase (LDH) at the end of glycolysis (Emhoff & Messonnier, 2023). The transportation of lactate between cells is intrinsically linked to the metabolic demand, with the production rate being dependent upon the rate of glycolytic activity (Rogatzki et al., 2015). Maximal muscular contraction is strongly glycolytically activating, which disturbs metabolic homeostasis, thus increasing the lactate efflux into other tissues (blood plasma, oxidative muscle fibres, and central organs) due to the increase in lactate and H^+ concentrations (Brooks et al., 1999).

Early studies described the utilisation of glycolysis based on blood lactate concentrations due to increasing metabolic demand (e.g., Margaria et al., 1933, Margaria et al., 1971; Jacobs et al., 1983), as well as the time constants of lactate distribution between the compartments (Zouloumian & Freund, 1981; Freund et al., 1984). However, quantification of metabolic energy derived from lactate accumulation in the blood is controversial, with several authors contesting the validity (Ferretti, 2015). This has stunted the progress of knowledge regarding the energetics of supramaximal exercise (Ferretti, 2015). Whilst significant lactate production occurs during steady state exercise, the majority is oxidised, therefore the $\dot{V}O_2$ accurately represents the energy contribution of 'aerobic glycolysis' (Brooks, 2012). Consequently, the net rise in the body lactate pooling represents the energy of non-oxidative glycolysis following supramaximal exercise (Brooks, 2012). Due to the rapid dissociation of lactate with total body water following maximal exercise the rise in blood lactate accumulation can be used to estimate non-oxidative glycolysis (Brooks, 2012).

Due to limited ability to store ATP (~5-8 mmol per kg of muscle) (Harris et al., 1974; Dawson, 1983), ATP must continually be resynthesised by the three energy systems. Applying specific rates of reactions and the concentrations of metabolites dependent upon; the individuals muscle mass, νLa_{max}, and oxidative capacity, Mader (1984; 2003; Mader & Heck, 1986) devised a mathematical model of human energy metabolism to understand the metabolic origin behind the MLSS. This systematic review will focus specifically on the νLa_{max} constructed by Mader (1984; Mader & Heck 1986) to denote the maximal glycolytic rate of the muscle. A recent overview and simplification of Mader's (1984) mathematical model of human energy metabolism has been provided by Wackerhage et al. (2022). Mader's (1984; 2003; Mader & Heck, 1986) model suggests the νLa_{max} as an important parameter in endurance performance, illustrating an inverse relationship between νLa_{max} and the MLSS.

1.2 Development of Mader's Maximal Lactate Accumulation Formula

Mader first proposed the maximal lactate formation rate as part of his mathematical model of human energy metabolism to identify the maximal rate of glycolysis within the muscle (Mader, 1984; Mader and Heck 1986; Mader, 2003). Mader (1984; Mader and Heck 1986) calculated the rate of ATP resynthesis via glycolysis using two key principles: 1) That an increased concentration of ADP (Adenosine diphosphate) and AMP (Adenosine monophosphate) activate the upregulation of glycolysis, whereas a reduction in pH inhibits phosphofructokinase (PFK) activity (Dobson et al., 1986), thus slowing down the glycolytic rate (Mader and Heck, 1986; Mader, 2003). 2) Lactate is always the product of glycolysis due to the near-equilibrium reaction of lactate dehydrogenase (LDH) (Sahlin et al., 1976; Rogatzki et al., 2015). These principles allowed Mader (1984; Mader & Heck, 1986) to calculate the maximum rate of glycolysis based on the maximum rate of lactate formation within the muscle cell (equation 1):

$$\text{Maximum lactate formation rate} = \frac{dLa}{dt}$$

Equation (1)

The maximal lactate formation rate within the muscle cannot be measured directly. Therefore, Mader (1994) proposed the utility of measuring blood lactate prior and post an all-out sprint test as an indirect measure of the maximal glycolytic flux (equation 2). Later, mathematical modelling from Heck et al. (2003) proposed an optimal test duration of 10 s due to the suppression of PFK activity with increasing acidosis the greater the exercise

duration. It should be noted the νLa$_{max}$ calculated from changes in peripheral blood lactate concentration, can only provide an estimate of the muscles maximal glycolytic flux, due to the complex dynamics of diffusion from the active muscle cell and elimination processes (Mader, 1994). Due to their interdependence the exact contribution of the alactic and glycolytic energy metabolism cannot be determined and is influenced by the intensity and duration of exercise (Heck et al., 2003). Whilst the alactic time represents a fictitious period, it is deemed necessary to avoid underestimating the νLa$_{max}$ (Nitzsche et al., 2018b). The time duration to achieve peak power is thought to be equal with the maximal alactic power (Heck et al., 2003).

$$\nu La_{max} = \frac{(BLa_{maxpost} - BLa_{pre})}{(t_{test} - t_{alac})}$$

Equation (2)

Maximal lactate accumulation rate formula νLa$_{max}$ (mmol · L^{-1}· s^{-1}) (Mader, 1994). BLa$_{maxpost}$ = maximum post-exercise blood lactate, BLa$_{pre}$ = blood lactate prior to the start of the test, t$_{test}$ = test duration, t$_{alac}$ = alactic time interval, fictitious time-period where no accumulation of blood lactate occurs.

Recent studies concerning the use of capillary blood sampling to estimate the νLa$_{max}$, have adjusted parameters of Mader's model or implemented precise recommendations dependent upon; the exercise modality (Quittmann et al., 2020; Haase et al., 2024), specific methods for determining the alactic time contribution (Dunst et al., 2023b; Meixner et al., 2024), test duration (Langley et al., 2024), and consideration of the oxidative metabolism (Yang et al., 2023). It is unclear after which specific time interval capillary blood should be sampled, and for what total duration post-exercise to reliably determine the maximum lactate attained (Sperlich et al., 2010; Nitzsche et al., 2018b; Quittmann et al., 2020; Dunst et al., 2023; Langley et al., 2024). Thus, this remains to be clarified. To allow accurate comparisons of results between studies a consensus regarding the most accurate, reliable, and valid measure of νLa$_{max}$ specific to each sporting modality need to be considered.

In addition to discrepancies in νLa$_{max}$ test protocols employed, currently, there is no agreed upon denotation of the maximal lactate accumulation rate measured via blood sampling. To-date a wide array of abbreviations, each with distinct connotations to the process involved have been reported including: dLa/dt max (Mader, 1984; Mader & Heck, 1986), V̇La'max (Mader, 1994), νla$_{,max}$ (Mader, 2003), V̇La$_{max}$ (Hauser et al., 2014), νLa$_{max}$ (Nitzsche et al., 2020; Meixner et al., 2024), ċLa$_{max}$ (Quittmann et al., 2022), v̇La$_{max}$ (Dunst et al., 2023a; 2023b), and νLa.max (Pohl et al., 2024). A common census is needed when discussing maximal lactate accumulation rate, to build cohesive research environment.

The primary aim of this systematic review is to evaluate the current methodological approaches applied to test an athletes νLa$_{max}$ within different exercise modalities. Secondary we aim to assess the reliability of the νLa$_{max}$ including the alactic time component, and the effects of training interventions. Subject to the review findings we aim to make practical recommendations for future researchers and applied practitioners. These recommendations should provide standardisation of test procedures allowing for accurate comparisons to be drawn, whilst aiming to enhance the reliability and validity of νLa$_{max}$ assessment. Lastly, we aim to provide a sound rationale for standardisation of an appropriate abbreviation when discussing maximal lactate accumulation rate.

2 Material and Methods

2.1 Search Strategy

This systematic review was conducted in accordance with the PRISMA (Preferred Reporting Items, for Systematic Reviews and meta – analyses) guidelines (Moher et al., 2009). A systematic literature search using the following databases, PubMed, SCOPUS, Google Scholar, and SPOLIT, was undertaken. As mentioned above Mader (1984) is widely recognised as the inception of the νLa_{max} formula, thus 1984 was used as the earliest available article. The search was conducted between 1984 until July 2024. All database searches were conducted between the 27th – 28th July 2024. The key search terms used were a combination of "νLa_{max}"; "maximal lactate"; "maximal lactate accumulation"; "maximal lactate accumulation rate"; "maximal lactate formation"; "maximal lactate production"; "maximal glycolytic rate"; "maximal glycolytic flux"; "all out exercise" AND "lactate"; "maximal exercise" AND "lactate accumulation"; "maximal lactate" AND "sprint"; "maximal lactate" AND "cycling"; "maximal lactate" AND "running"; "maximal lactate" AND "swimming"; "maximal lactate" AND "rowing", and the German equivalence.

Therefore, a total of 14 separate searches were conducted across each of the databases. In addition, a reverse search of all papers which have citied Mader's (1984) seminal paper were undertaken using Google Scholar's 'cited by' tool. Furthermore, the same reverse strategy was applied for Heck et al. (2003) paper from which the νLa_{max} formula is frequently cited. All titles and abstracts were examined and screened for eligibility. Screening the reference lists of eligible studies identified an additional four articles. Articles were searched for studies on humans, free full text in either English or German, and published between our date range of 1984 – July 2024.

Articles were pooled together from the four databases and screened as one succinct list. Literature search, identification, and review was conducted by all four authors (JL, NN, RH, MP). Articles were screened at every stage by at least two of this manuscript's authors for eligibility, following the procedure outlined in Figure 1. Any disagreements between authors were resolved by the consensus of the other authors.

2.2 Inclusion and Exclusion criteria

Pre-determined inclusion and exclusion criteria were followed during screening. 1) Original studies using the νLa_{max} formula, 2) written in the English or German language, and 3) exercise duration less than 60 s were included. Whereas original articles that used or mentioned the following were excluded; 1) non-human populations, 2) clinical populations, 3) not in vitro, and 4) mentions of other lactate protocols (maximum lactate steady state), 5) articles that have not been peer reviewed or not original data (systematic review, meta-analysis, conference abstract, postgraduate thesis, book) 6) articles that were primarily mathematical simulations rather than human participants.

2.3 Data Extraction and Analysis

Full text of all included articles were read and the study design, sample size, test duration, exercise modality, νLa_{max} formula, methodological considerations, and main conclusion, were extracted and summarised in Tables 1 - 3. There was no blinding to study author, institution, or journal at this stage. Data extraction was carried out by JL, RH, and MP, where NN checked the extracted data for accuracy and totality.

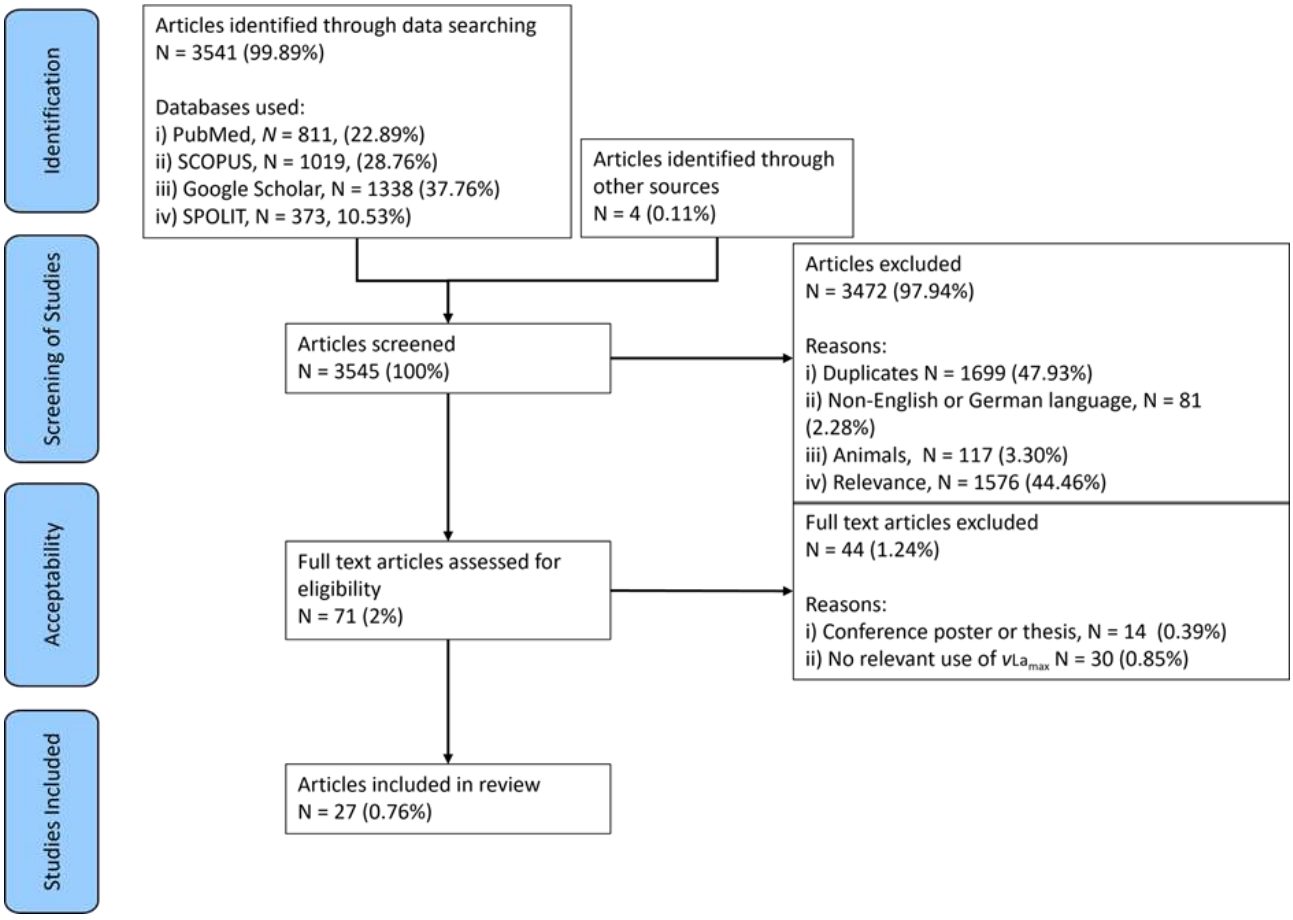


Figure 1. Study selection criteria for systematic review.

3 Results

Our comprehensive literature search and screening process identified twenty-seven articles that described the use of the νLamax formula within their methods, outlined in Table 1. The four main outcomes for screening the articles were: what alactic method within the νLamax formula was used, exercise duration, exercise modality, and specific methodological considerations. Additionally, studies that assessed the νLamax reliability (Table 2), and training intervention studies (Table 3) were included.

The literature collectively uses the Mader's (1994) νLamax formula, whilst the alactic component of the equation is commonly modified. In total nine different methods to determine the alactic time span were identified across 27 studies including;

- time to peak power (N = 6),
- time to decline of 3.5% in peak power output (N = 11),
- exercise test duration (s) · 0.0909 + 2.0455 (N = 4),
- fixed time intervals of 3- (N = 2), 3.5- (N = 3), 4- (N = 2), and 5 s (N = 1) after the onset of the sprint,
- time to peak plus oxidative component (N = 1) and the time of fatigue-free force velocity profile (N = 2).

Table 1. Articles that have tested an athletes νLa_{max}.

Identifier	Sample Size and Gender	Training Status	Modality	Test Duration/ distance	Alactic time period	νLa_{max} data	BLC Sampling	Summary
Hauser et al. 2014	N = 13 (M13)	Amateur	Cycling	15s	TTP-3.5%	0.91 ± 0.18	0-9 mins every 1 min	
Adam et al. 2015	N = 23 (6F M17)	Amateur	Cycling	15s	TTP-3.5%	0.72 ± 0.13 (T1) 0.72 ± 0.14 (T2) 0.70 ± 0.14 (T3)	Every 1 min for 10 mins	
Manunzio et al. 2016	N = 4 (M4)	Well Trained	Cycling	15s	TTP	0.54 ± 0.16 (120rpm T1) 0.56 ± 0.16 (120rpm T2) 0.46 ± 0.11 (120rpm T3)	Every 1min for 10 mins	
Yang et al. 2023	N = 10 (M10)	Elite Track	Cycling	15s	TTP-3.5% TTP TTP+tOxi	0.97 ± 0.18 0.85 ± 0.12 0.88 ± 0.13	0-10 mins every 1 min	Only one to use oxid
Dunst et al. 2023a	N = 12 (F3 M9)	Elite Track	Cycling	3s 8s 12s	tFf	0.70 0.76 0.78	0, 1, 3, 5, 7, 10, 15, 20, 25, 30 mins	
Dunst et al. 2023b	N = 9 (M9)	Elite Track	Cycling	3s 8s 12s 60s	tFf	0.70 0.80 0.82 0.31	0, 1, 3, 5, 7, 10, 15, 20, 25, 30 mins	
Harnish et al. 2023	N = 20 (F12 M18)	Amateur	Cycling	15s	TTP-3.5%	0.67 ± 0.02 (T1) 0.64 ± 0.24 (T2)	Every 2 mins from 60s until peak minus 1 mmol · L^{-1}	
Poffé et al. 2024	N = 31 (F12 M19)	Recreational (17), Amateur (10) to Elite (4)	Cycling	15s	TTP-3.5%	0.56 ± 0.15 (130rpm)	Every 1min for 10 mins	
Meixner et al. 2024	N = 50 (F20 M30)	Amateur	Cycling	15s	TTP-3.5s TTP TTP-3.5%	0.55 ± 0.14 (T1) 0.54 ± 0.13 (T2) 0.50 ± 0.11 (T1) 0.49 ± 0.13 (T2) 0.56 ± 0.13 (T1) 0.53 ± 0.14 (T2)	Every 1min for 10 mins	
Haase et al. 2024	N = 13 (M13)	Amateur	Cycling	10s	3s	0.63 ± 0.14 (T1 - 90rpm) 0.76 ± 0.13 (T2 - 110rpm) 0.86 ± 0.16 (T3 - 130rpm) 0.88 ± 0.15 (T4 - 150rpm) 0.94 ± 0.14 (T5 - 170rpm)	30 s interval until 9 mins, 1 min intervals until 15 mins and 17, 19, 21, 24, 27, 30 mins	

Langley et al. 2024	N = 15 (M15)	Well Trained	Cycling	10s 15s 30s	TTP-3.5%	0.86 ± 0.17 (10s) 0.68 ± 0.18 (15s) 0.45 ± 0.07 (30s)	Every 1min for 10 mins	
Quittmann et al. 2021b	N = 18 (3F 15M)	Amateur Triathlete	Cycling / Running	15s	TTP-3.5%	0.60 ± 0.16 (T1 CYC) 0.60 ± 0.15 (T2 CYC) 0.72 ± 0.16 (T1 100m run) 0.71 ± 0.16 (T2 100m run)	Every 1 min for 10 mins	
Nitzsche et al. 2018a	N = 14 (M14)	Amateur	Cycling / IFL	CY - 15s IFL - 16.1 ± 2.0s (10 reps)	TTP-3.5% (CY) TTP-3.5% (IFL)	0.81 ± 0.09 0.28 ± 0.09	30 s interval until 3 mins, 1 min interval until 9 mins	
Quittmann et al. 2021a	N = 18 (F3 M15)	National Triathletes	Cycling/ Handcycling	15s	TTP	0.53 ± 0.14 (T1 CYC) 0.52 ± 0.14 (T2 CYC) 0.31 ± 0.09 (T1 HCY) 0.32 ± 0.10 (T2 HCY)	Every 1min for 10 mins	
Hanon et al. 2011	N = 25 (F6 M19)	Amateur	Running	15s		0.47 ± 0.06 (Amateur) 0.59 ± 0.11 (Elite)	0- & 4-mins post	Predicting νLa_{max}
Wawer et al. 2020	N = 73 (F12 M61)	University Students	Running	8-14s	TTP	0.65 ± 0.23 (8s Tk T1a) 0.64 ± 0.22 (8s Tk T1b) 0.61 ± 0.23 (10s Tk T1a) 0.56 ± 0.19 (10s Tk T1b) 0.60 ± 0.22 (12s TK T1a) 0.60 ± 0.21 (12s TK T1b) 0.60 ± 0.19 (14s TK T1a) 0.59 ± 0.19 (14s TK T1b) 0.84 ± 0.15 (10s Trm T 2a) 0.83 ± 0.22 (10s Trm T2b) 0.91 ± 0.17 (12s Trm T2a) 0.91 ± 0.18 (12s Trm T2b) 0.74 ± 0.21 (10s TK T3a) 0.71 ± 0.20 (10s Trm T3b)	0-10 mins every 1min	
Quittmann et al. 2020	N = 16 (F5 M11)	Competitive MD	Running	13.90 ± 1.42s 13.89 ± 1.47s 13.86 ± 1.47s	tExer · 0.0909 + 2.0455	0.79 ±0.18 (100m)	Every 1 min for 10 mins	
Quittmann et al. 2023	N = 44 (F15 M29)		Running		tExer · 0.0909 + 2.0455	0.74 ± 0.14 (M) 0.55 ± 0.13 (F)	Every 1 min for 10 mins	

Thron et al. 2024	N = 34 (F15 M19)	Recreational	Running	100m	TTP	0.92 ± 0.20 (100m athletes) 0.83 ± 0.16 (400m athletes) 0.71 ± 0.13 (800m athletes)	Every 1 min for 10 mins
Pohl et al. 2024	N = 21 (F8 M13)		Running		tExer · 0.0909 + 2.0455	0.59 ± 0.09 (Baseline) 0.51 ± 0.01 (High BLC) 0.53 ± 0.10 (CHO Low) 0.54 ± 0.10 (CHO High) 0.57 ± 0.10 (CHO Acute)	Every 1 min for 10 mins
Schünemann et al. 2023	N = 10 (F3 M7)	National level	Rowing	10s	tExer · 0.0909 + 2.0455	0.45 ± 0.14	0-10 mins every 1 min
Held et al. 2024	N = 17 (F8 M9)	Amateur	Rowing	20s	4s	0.29 ± 0.11 (T1) 0.28 ± 0.10 (T2)	Every 1 min for 10 mins
Nitzsche et al. 2018b	N = 32 (M32)	University Students	Isokinetic Force Loads	8 reps T1: 12.1 ± 1.02s T2: 11.5 ± 1.03s 16 reps T1: 23.1 ± 0.31s T2: 23.0 ± 0.28s	TTP-3.5%	0.25 ± 0.11 (T1 8reps) 0.27 ± 0.11 (T2 8reps) 0.27 ± 0.07 (T1 16reps) 0.26 ± 0.07 (T2 16reps)	30s interval until 3 mins, 1 min interval until 9 mins
Nitzsche et al. 2020	N = 24 (M24)	University Students	Isokinetic Force Loads	10 reps (15s)	3s	0.27 ± 0.07 (T1 HVLL) 0.30 ± 0.07 (T2 HVLL) 0.25 ± 0.12 (T1 LVHL) 0.29 ± 0.09 (T2 LVHL)	30s interval until 3mins, 1 min interval until 9 mins
Zwingmann et al. 2020	N = 8 (M8)	National	Canoe polo	15s	3.5s	0.58 ± 0.10	Every 1 min for 10 mins
Quittmann et al. 2018	N = 12 (M12)	National Triathletes	Handcycling	15s	TTP-3.5%	0.45 ± 0.11	Every 1 min for 10 mins
Mavroudi et al. 2023	N =14 (F6 M8)	Semi Elite	Swimming	25m: 11.75 ± 1.38 35m: 17.76 ± 2.04 50m: 26.78 ± 3.21	3.5s 4s 5s	0.75 ± 0.18 0.54 ± 0.18 0.49 ± 0.16	every minute until peak

Legend: RCT; randomised control trial, CS; case study, T; Trial, IFL; Isokinetic Force Load, CYC; Cycling, CHO; Carbohydrate, RPM; Revolutions per minute, min; minute, s; Seconds, M; Males, F; Females, HVLL; high volume low load, LVHL; low volume high load, tFf; time fatigue free force, tExer, time to finish the test/exercise, TTP; Time to Peak Power, TTP-3.5%; time until peak power dropped by 3.5 %, TK; track, Trm; Treadmill, MD; Middle distance, HCY; Handcycling, BLC; Blood lactate concentration, N; Sample size, %; Percentage, $\dot{v}La_{max}$; maximal lactate accumulation rate.

Table 2. Articles investigating the νLa_{max} reliability and/or variability.

Identifier	Sample Size and Gender	Training Status	Modality	Test Duration/ distance	Alactic time-period	Reliability/Variability results - t_{alac}	Reliability/Variability results – νLa_{max}	Reliability/Variability results – BLC
Adam et al. 2015	N = 23 (6F M17)	Amateur	Cycling	15s	TTP-3.5%	ICC = 0.881; RMSE= 0.25; CV = 5.8%	ICC = 0.904; RMSE = 0.045; CV = 6.3%	BLC_{pre}: ICC = 0.804; RMSE = 0.20 mmol · L^{-1}; CV = 18.8 % BLC_{peak}: ICC = 0.856; RMSE = 0.58; CV = 6.8 % ΔBLC: ICC = 0.891; RMSE = 0.52; CV = 7.0 %
Harnish et al. 2023	N = 20 (F12 M18)	Amateur	Cycling	15s	TTP-3.5%	CV = 38.3%	ICC = 0.66; CV = 18.6%	BLC_{pre}: CV = 45.6 % BLC_{peak}: CV = 23.3 %
Meixner et al. 2024	N = 50 (F20 M30)	Amateur	Cycling	15s	3.5s TTP TTP-3.5%	3.5s: fixed TTP: ICC = 0.41; SEM = 0.71; CV = 30% TTP-3.5%: ICC = 0.52; SEM = 1.83; CV = 51%	3.5s: ICC = 0.91; SEM = 0.02; CV = 3.1% TTP: ICC = 0.87; SEM = 0.06; CV = 12.1% TTP-3.5%: ICC = 0.79; SEM = 0.15; CV = 26.4%	ΔBLC: ICC = 0.911; SEM = 0.22; CV = 3.6 %
Quittmann et al. 2021b	N = 18 (3F 15M)	Amateur Triathlete	Cycling / Running	15s	TTP-3.5%	CYC: ICC = 0.592 100 m run: ICC = 0.242	CYC: ICC = 0.894; Bias (LoA) = -0.003 (-0.149 to 0.143) 100 m run: ICC = 0.868; Bias (LoA) = -0.022 (-0.181 to 0.137)	CYC: BLC_{pre}: ICC = 0.537 BLC_{peak}: ICC = 0.870 ΔBLC: ICC = 0.867 100m run: BLC_{pre}: ICC = 0.335 BLC_{peak}: ICC = 0.808 ΔBLC: ICC = 0.783
Quittmann et al. 2021a	N =18 (F3 M15)	National Triathletes	Cycling/ Handcycling	15s	TTP	CYC: ICC = 0.525 HCY: ICC = -0.115	CYC: ICC = 0.872; LoA = -0.15 to 0.14 HCY: ICC = 0.828; LoA = -0.10 to 0.12	
Nitzsche et al. 2018b	N = 32 (M32)	University Students	Isokinetic Force Loads	8 reps T1: 12.1 ± 1.02s T2: 11.5 ± 1.03s 16 reps T1: 23.1 ± 0.31s T2: 23.0 ± 0.28s	TTP-3.5%	8 reps: r = 0.67; Bias (LoA) = -0.02 (Median) (-0.33 to 1.96) s 16 reps: r = 0.48; Bias (LoA) = 0.11 (-6.59 to 6.81) s	8 reps: r = 0.72; Bias (LoA) = 0.02 (-0.09 to 0.13) 16 reps: r = 0.68; Bias (LoA) = -0.008 (-0.118 to 0.102)	BLC_{peak}: 8 reps: r = 0.688; 16 reps: r = 0.821

Held et al. 2024	N = 17 (F8 M9)	Amateur	Rowing	20s	4s	-	ICC = 0.85; SEM = 0.02	BLC_{peak}: ICC = 0.88; SEM = 0.3
Wawer et al. 2020	N = 73 (F12 M61)	University Students	Running	8-14s	TTP	8s Tk: ICC = 0.73, CV = 11.1% 10s Tk: ICC = 0.16, CV = 10.1% 12s TK: ICC = 0.76, CV = 8.7% 14s TK: ICC = 0.11, CV = 10% 10s Trm: ICC = 0.47, CV = 10.2% 12s Trm: ICC = 0.26, CV = 7.8%	8s Tk: ICC = 0.89, CV = 9.8% 10s Tk: ICC = 0.82, CV = 12.9% 12s TK: ICC = 0.92, CV = 9.0% 14s TK: ICC = 0.84, CV = 10.7% 10s Trm: ICC = 0.76, CV = 7.6% 12s Trm: ICC = 0.79, CV = 6.1%	10s Trm: BLC_{peak}: ICC = 0.91; CV = 5.2 % 12s Trm: BLC_{peak}: ICC = 0.77; CV = 5.8 %

Legend: BLC_{pre}; blood lactate concentration pre-test, BLC_{peak}; peak blood lactate concentration post-test, ΔBLC; change of blood lactate concentration (BLC_{peak} - BLC_{pre}), CV; coefficient of variation, CYC; Cycling, F; Female, HCY, Handcycling, ICC; Intraclass correlation coefficient, LoA; Limits of Agreement, M; Male, min; minute, N; Sample size, r; Pearson's r correlation coefficient, reps; repetitions, RMSE; Root Mean Square Error, s; seconds, SEM; Standard Error of Measurement, T; Trial, TK; track, Trm; Treadmill, TTP; Time to Peak, TTP-3.5%; time until peak power dropped by 3.5 %, νLa_{max}; maximal lactate accumulation rate, %; Percentage.

Table 3. Articles that have measured the adaptation of νLa_{max} following a training intervention.

Identifier	Sample Size and Gender	Training Status	Modality	Test Duration/ distance	Alactic time-period	Training Intervention	Sessions per week	Duration (weeks)	νLa_{max}	$\Delta\nu La_{max}$
Hommel et al. 2019	N = 30 (M, 10 per group)	amateur cyclists	Cycling	15s	TTP-3.5%	SIT: not standardized ET: not standardized	3	6	Pre – SIT: 0.76 (0.18) ET: 0.75 (0.18) Post – SIT: 0.63 (0.15) ET: 0.74 (0.17)	SIT: -10.53%, sig. reduction (-0.08 ($p < 0.05$)) ET: -1.35%, no sig. changes
Nitzsche et al. 2020	N = 24 (M, HVLL = 14; LVHL = 10)	healthy strength trained	Isokinetic Force Loads	10 reps (15s)	3 s	5 sets per exercise, 90 s break HVLL: as much repetitions as possible at 50% 1RM LVHL: 10 repetitions at 70% 1RM Exercises: leg press, leg extension, leg flexor (prone position)	3	6	Pre – HVLL: 0.271 (0.067) LVHL: 0.249 (0.122) Post – HVLL: 0.298 (0.067) LVHL: 0.291 (0.089)	HVLL: +9.96% ($p = 0.022$, $d = 0.406$), LVHL: +16.87% ($p = 0.233$, $d = 0.384$)

Legend: ET; endurance training, HVLL; high volume low load, LVHL; low volume high load, M; Male, N; Sample size, 1RM; one repetition maximum, reps; repetitions, s; seconds, SIT; sprint interval training, TTP-3.5%; time until peak power dropped by 3.5 %, νLa_{max}; maximal lactate accumulation rate, %; Percentage.

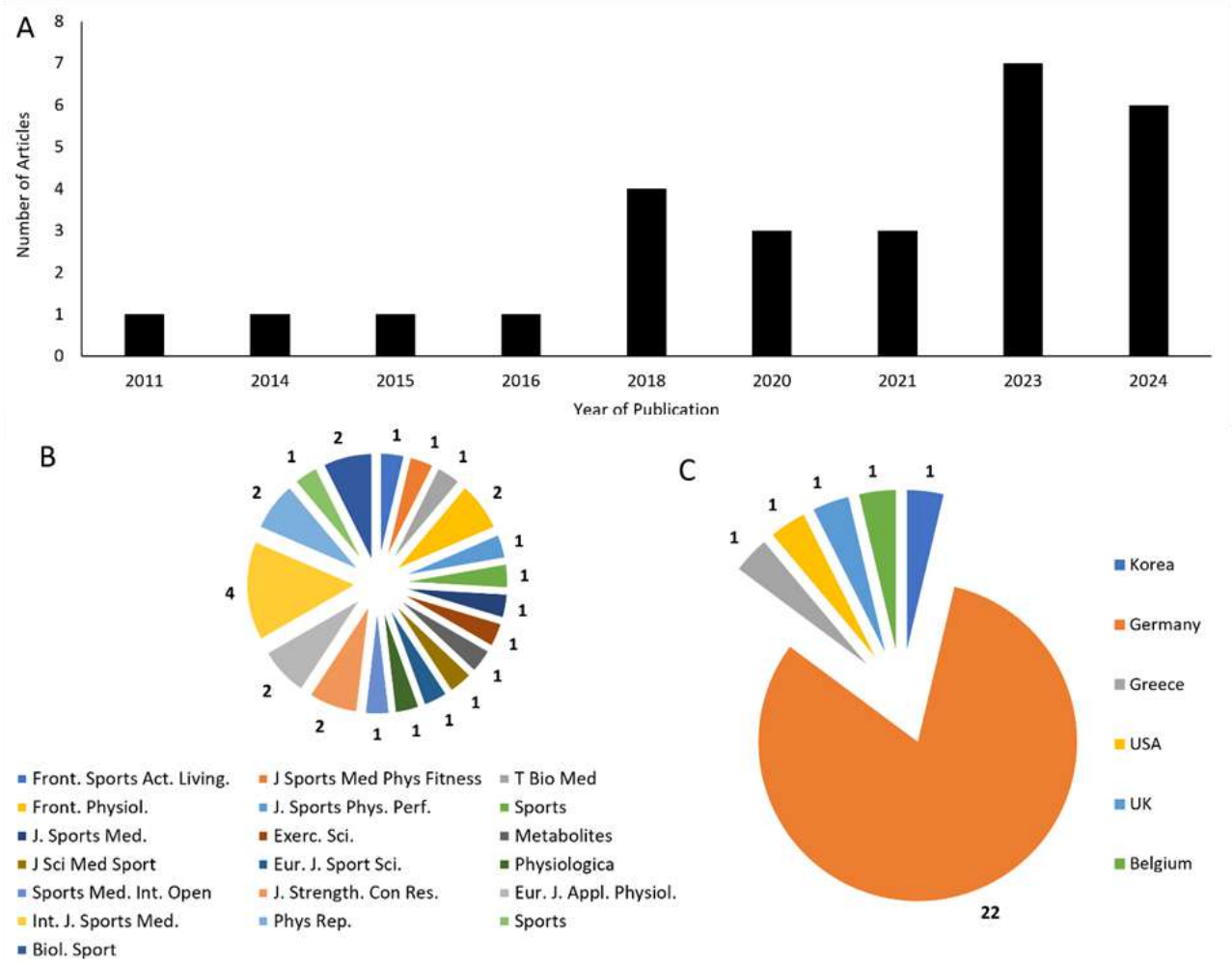


Figure 2. Summary of the article extracted for this review (N = 27). A- Distribution of articles via year the articles were published, B- Distribution of articles via journal of publication, C- Distribution of articles via first author country of origin.

From the included articles νLa_{max} was tested across several different populations of varying performance levels, ages, sex, and across an array of modalities. The included articles spanned from 2011 to and including 2024 (Figure 2A). The articles were published in a variety of journals with no conceivable pattern (Figure 2B). The articles were authored primarily by German based researchers (22 in total), with the remaining from Belgium, Korea, Greece, UK, and the USA (Figure 2C; (Hauser et al., 2014, Adam et al., 2015, Manunzio et al., 2016, Yang et al., 2023, Dunst et al., 2023a, Dunst et al., 2023b, Harnish et al., 2023, Poffé et al., 2024, Meixner et al., 2024, Haase et al., 2024, Langley et al., 2024, Quittmann et al., 2021b, Nitzsche et al., 2018a, Quittmann et al., 2021a, Hanon et al., 2011, Wawer et al., 2020, Quittmann et al., 2020, Quittmann et al., 2023, Thron et al., 2024, Pohl et al., 2024, Schünemann et al., 2023, Held et al., 2024, Nitzsche et al., 2018b, Nitzsche et al., 2020, Zwingmann et al., 2020, Quittmann et al., 2018b, Mavroudi et al., 2023). A total sample size outlined was N = 580, with (N = 452) coming from amateur, well-trained (N = 63), and elite (N = 65) participants (as outlined by journal reported demographics), whereby 129 of the 580 participants were female (22.24%) and the other 451 participants were male (77.76%). The average age of the participants was 23 years of age, with two studies using populations under the age of 18 years old (11–15-year-olds). Seven different modalities were tested – cycling (N = 14), swimming (N = 1), running (N = 7), handcycling (N = 2), kayaking

(N = 1), rowing (N = 2), and Isokinetic force load (N = 3). Studies were included twice if they tested multiple modalities. Exercise duration ranged from 3 to 60 seconds, with the most popular test duration of 15 s (N = 15). Additionally, a variety of study designs were outlined, 17 studies were classified as cohort studies, 8 papers identified reliability and 2 papers identified the effects of training interventions on νLa_{max}.

Time to peak blood lactate concentration ($tBLC_{max}$) is a key variable for νLa_{max} research, yet only 6 of the 27 studies documented their respective $tBLC_{max}$. Within cycling research articles, νLa_{max} test durations of 10, 15, and 30 s elicit $tBLC_{max}$ durations of 5 ± 2 mins, 4.36 ± 2.4 mins, and 7 ± 2 mins, respectively. An average $tBLC_{max}$ for Isokinetic force νLa_{max} tests were 2.31 ± 0.7 mins. Additionally, a 20 s rowing νLa_{max} test elicited average $tBLC_{max}$ values of 5.15 ± 0.5 mins. Lastly, swimming νLa_{max} tests of 25 m, 35 m, and 50 m elicited $tBLC_{max}$ values of 2.2 ± 0.8 mins, 2.1 ± 0.7 mins, and 2.4 ± 1.0 mins, respectively.

4 Discussion

This systematic review examined all published research applying the νLa_{max} within exercise durations <60 s and in human populations since its inception 40 years ago by Mader (1984). A total of 27 studies including 580 participants were included within the analysis across seven different modalities spanning test durations of 3 - 60 s. Additionally, this review evaluated the alactic time component, test duration, modality, reliability, training interventions, blood lactate sampling period, on the νLa_{max} and proposed future test recommendations.

Over the last 40 years, the literature discussing the maximal lactate accumulation rate has used a wide variety of abbreviations, each having distinct connotations to the process in question. The most common terminologies used when discussing maximal lactate accumulation rate are; dLa/dt max (Mader, 1984; Mader & Heck, 1986), $\dot{V}La'max$ (Mader, 1994), $\nu La_{,max}$ (Mader, 2003), $\dot{V}La_{max}$ (Hauser et al., 2014), νLa_{max} (Nitzsche et al., 2020; Meixner et al., 2024), $\dot{c}La_{max}$ (Quittmann et al., 2022), $\dot{\nu}La_{max}$ (Dunst et al., 2023a; 2023b), vLa.max (Pohl et al., 2024), and recently $\nu Lapeak$ (Wackerhage et al., 2025). The rate of glycolysis is activated as a function of free ADP and AMP, which in turn regulates the rate of PFK. The 'ν' denotes the rate of the reaction in accordance with the Michaelis-Menten Kinetics (Michaelis & Menten, 1913; Cornish-Bowden, 2014). It should be noted that the use of the 'ν' does not imply that the actual reaction rate is measured during the all-out sprint tests. The term La_{max}/La_{peak} denotes the highest lactate accumulation in the blood post exercise. The term 'νLapeak' has been suggested due to the unlikely occurrence PFK activity and thus glycolysis is maximally activated in vivo due to decrease in pH during all out exercise inhibiting the PFK activity (Dobson et al., 1986) and ADP/AMP concentrations being unlikely to rise high enough to maximally elicit PFK activity (Wackerhage et al., 2025). Additionally, the peak rate of glycolysis and lactate synthesis only occurs for a short time-period prior to declining, therefore the maximal rate of glycolysis is not sustained over the time-course of the exercise (Mader et al., 2002; Heck et al., 2003; Porter & Langley, 2025). A common census is needed when discussing maximal lactate accumulation rate, to build cohesive research environment.

4.1 Alactic time

The alactic time span is considered to reflect the "lactate-free period" where accumulation of lactate in the blood is negligible (Mader, 1994). Whilst a timespan where no glycolytic activity occurs is fictitious (Brooks, 2018;

Chung et al., 1998), the alactic period represents a crucial element of the νLamax calculation with the exclusion leading to underestimating the νLamax (Nitzsche et al., 2018b). As the alactic time is used to determine the denominator in the νLamax equation variations significantly influence the νLamax, with a variation of 1 second influencing the νLamax by up to 26% when assessed via a 15 s sprint (Hauser, 2014). Therefore, a valid and reliable method to identify the alactic time is essential.

Currently, nine methods to determine the alactic period have been applied with varying approaches both within and between modalities (Table 1). Figure 3 highlights the influence of the alactic method on the νLamax over a 15 s cycling test. Unsurprisingly, a strong correlation between νLamax and alactic durations were observed (Figure 3). On average, TTP-3.5% produced the longest alactic time (4.16 ± 0.61 s), compared with a fixed time of 3.5 s, and TTP (2.75 ± 0.49 s). Yang et al. (2023) results were excluded from the group linear analysis, due to higher peak νLamax values likely attributed by the elite population (national level sprint cyclists). Yang et al. (2023) results observe the same trend in νLamax and alactic duration. The longest alactic time was associated with TTP-3.5% (3.28 ± 1.08 s) compared with TTP + oxidative time (2.24 ± 0.84 s), and TTP (1.75 ± 0.59 s) (Figure 3).

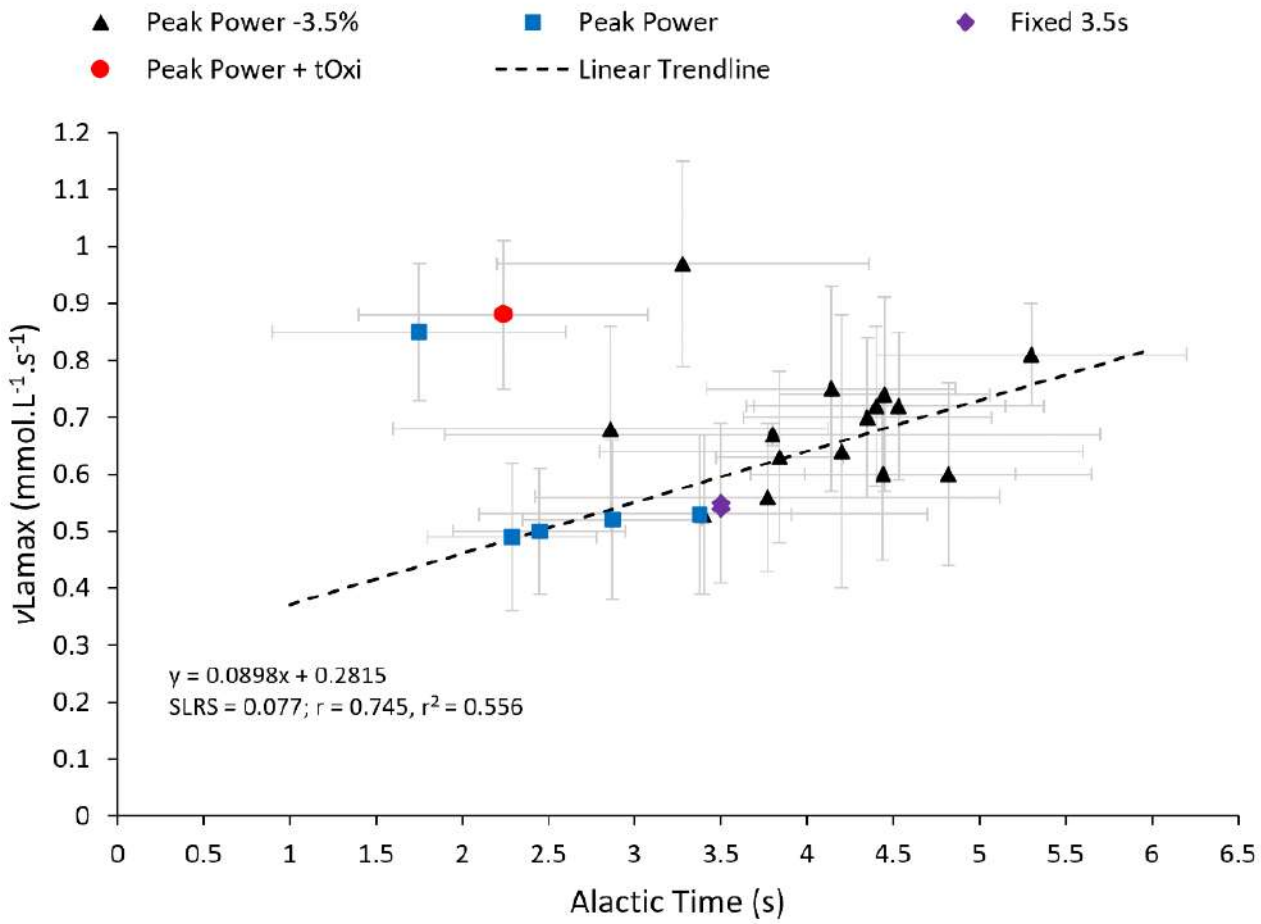


Figure 3. The relationship between the alactic method and νLamax assessed via 15 s all-out cycle ergometry testing. Individual markers represent the mean νLamax reported within each study (n = 20). Vertical error bars denote νLamax standard deviation. Horizontal error bars denote alactic time standard deviation. * *Note Yang et al. 2023 (n = 3) results were excluded from the linear regression.*

The alactic time-period is thought to be identical to the TTP, with researchers aiming to identify the corresponding period (Heck et al., 2003). Subsequently, the alactic method 'TTP-3.5%' was introduced to account for a 2.5% measurement error of the SRM power meter (Weber, 2003). Fixed duration alactic timespans are derived from Heck et al's. (2003) computer simulation models. Heck et al. (2003) reports that the alactic interval to be dependent upon test duration, with the alactic period of 3, 4, and 8 s corresponding to test durations of 10.5, 21.5, and 45 s, respectively. Dependent on the method of determination, modality, and participant population the reliability of the alactic time-period assessed via intraclass correlation coefficient (ICC) ranged from good (0.881) to poor (0.115) (Table 2). Within cycling the reliability of the TTP-3.5% was moderate to good (TTP-3.5% ICC: 0.52 - 0.881), and only poor to moderate TTP (ICC: 0.41 – 0.525) (Table 2). Applying a fixed alactic time overcomes the reliability challenges. A fixed time interval has been demonstrated to enhance the ICC (0.91) of the νLa_{max} results compared with alactic methods; TTP (ICC = 0.87), and tPP-3.5% (ICC = 0.79) (Meixner et al., 2024).

However, there are distinct limitations of applying a fixed time interval dependent on the test duration. [1)] To accurately determine the maximal glycolytic flux of an athlete, exercise should be all-out in nature with no pacing strategies employed. Therefore, all-out maximal exercise independent of test duration should provoke the same alactic timespan. Moreover, if an athlete is employing pacing strategies the test duration is too long. [2)] A fixed alactic timespan is not reflective of the individual's physiology. An individual's muscle fibre typology may influence the alactic time-duration with athletes who possess a higher percentage of type II fibres able to metabolise more PCr and yield ATP more rapidly than athletes with high percentages of type I fibres (Esbjornsson-Liljedahl et al., 1999; Greenhaff et al., 1994).

As the alactic time-period reflects a fictitious timespan where no glycolytic activity occurs (Brooks, 2018; Chung et al., 1998), an alternative approach of negating the alactic timespan from the νLa_{max} equation could be employed. Such an approach would enhance the reliability of the νLa_{max} in line with applying a fixed time-period as reported by Meixner et al., (2024). However, it should be considered that removing the alactic timespan would reduce the calculated νLa_{max} as the denominator in the equation would be increased. Subsequently, removing the alactic timespan may underestimate the maximal glycolytic rate (Nitzsche et al., 2018b) and subsequently increase the calculated maximal lactate steady state when employing Mader's model of human energy metabolism (Mader, 1984; Mader & Heck, 1986; Mader, 2003; Hauser et al., 2014; Wackerhage et al., 2023; Poffé et al., 2024).

Recently, Dunst et al. (2023) has proposed an attractive alternative for measuring the alactic period within cycling derived from the individual's fatigue-free force velocity profile. In cycling the power output is reflected by the parabolic relationship between mechanical force and pedaling rate. Subsequently, if the initial inertia resistance is set too low the time to achieve peak power will be reduced underestimating the alactic timespan. Contrary, if the inertia resistance is too high the time to achieve peak power will be extended and the alactic timespan overestimated (Dunst et al. 2023a). Dunst et al. (2023a) proposes the time point of the first systematic deviation from the fatigue-free force velocity profile should identify the alactic timespan by reflecting the end of maximal energy flux and should correspond with a non-significant accumulation of blood lactate. A valid force-

velocity profile can be derived from testing at the two extreme ends of the F/v profile (Sašek et al., 2022). Dunst et al. (2023a) utilised a motoric 6 s sprint against the lowest cycling resistance possible to attain maximal cadence and the initial 3-4 pedal revolutions during the all-out sprint to generate the fatigue-free force-velocity and power-velocity profiles. The time of fatigue free force (tFf) was defined as, 'the time where the force-velocity profile decreased below the fatigue-free maximum and never returned'. Extrapolating the linear regression of the ΔBLC from the 3, 8, and 12 s sprints, to a time point where no ΔBLC occurs correlated closely with tFf and used to validate this approach.

Whilst Dunst et al. (2023a) tFf provides a potential individualised measure of the alactic timespan in cycling, this approach cannot easily be applied to other modalities where force and velocity cannot be accurately and reliably sampled at a high frequency. Whereas Dunst et al's. (2023a) approach to validate the model may provide a simple and effective method to identify the alactic timespan applicable across modalities. Measurement of ΔBLC following two or more maximal all-out efforts of ≤12 s, and the extrapolation of a simple linear regression to the time point of no accumulation of blood lactate may be used to identify the alactic timespan (Dunst et al. 2023a).

The regression analysis method used by Nitzsche et al. (2017) to determine t_{alac} during isokinetic force loads also appears to be helpful. The procedure is based on several tests with different load times to determine the respective BLC_{peak} and the pre-load blood lactate concentration associated with the test; after plotting the BLC_{peak} against the test time, a regression line is used to determine the intersection with the regression line of the pre-load blood lactate concentrations (BLC) (Figure 4). The intersection point then indicates the end of the fictitious lactate-free interval and the beginning of increased lactate accumulations. This procedure is based on a method from Danforth (1965), in which the kinetics of PCr and muscle lactate were calculated (Mader 2015).

Presently, no sound recommendations of the 'gold standard' method in identifying the alactic time can be provided. Dunst et al. (2023a) tFf model has only been validated for a small population of elite track sprint cyclists who demonstrated linear F/v profiles. This approach needs to be validated across wider population pools, and the potential application across modalities investigated. Additionally, the reliability of this new approach has yet to be verified and requires further research. Likewise, further studies investigating the reliability and validity of the application of linear regression from maximal BLC are required. In the absence of a validated alactic method of determination we advocate for the adoption of a fixed alactic timespan to enhance the reliability of the νLa_{max}. In accordance with Dunst et al. (2023b) and Nitzsche et al. (2017) experimental findings, Heck et al. (2003) computer simulations and Quittmann et al. (2020) interpolation identify an alactic timespan of ~3 s to be appropriate for a 10 s test duration.

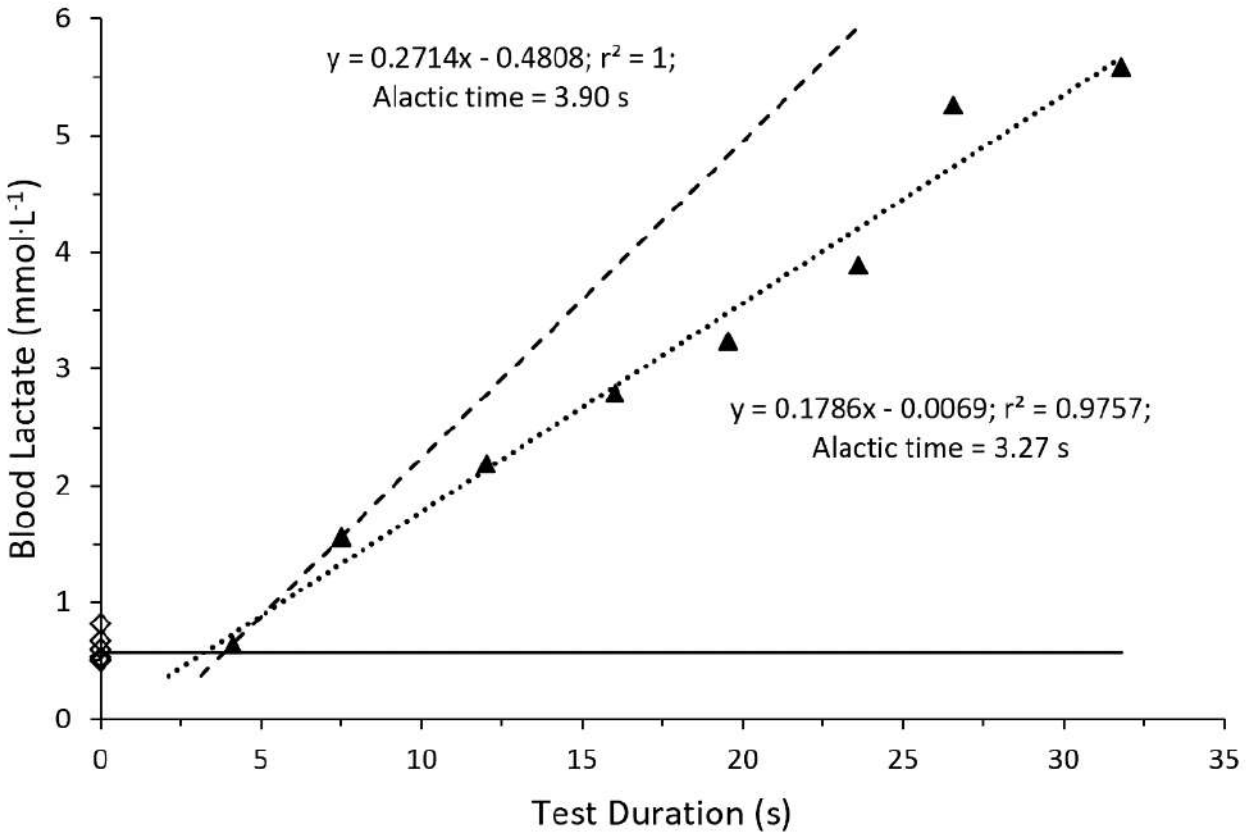


Figure 4. Linear regression analysis of blood lactate concentrations (black triangles) to identify the alactic time-period, sample data from a male test subject adapted from (Nitzsche et al., 2017). Maximal BLC measured over various maximum isokinetic strength tests with different load times at an angular velocity of 120°s^{-1}. The solid parallel line to the x-axis represents the mean resting blood lactate values. The short-dashed line represents the regression calculated from all BLC. The intercept of the regression for all blood lactate concentration is at 3.27 s and represents the end of the alactic time interval. The intercept denotes the time where no significant increase in blood lactate concentration occurs prior to this point (Nitzsche et al., 2017). The larger dashed line represents the regression from BLC of the first two test durations (4.13 and 7.52 s) where the intersect occurs at 3.90 s.

4.2 The Influence of Oxidative Contribution

For the most accurate determination of an individual's νLa_{max}, the interactions of all three energy systems need to be considered. Recently, Yang et al. (2023) demonstrated the importance of factoring in the oxidative metabolic component within the νLa_{max} equation during 15 s all-out cycling (Equation 3). Whilst Yang et al. (2023) only observed a small oxidative contribution (3.13 ± 1.61%) of the total energy supplied over the 15 s sprint, this significantly (p < 0.0001) increased the νLa_{max} (ES d = 0.23). Over a 100 m sprint the oxidative metabolism has been demonstrated to contribute ~10% of the total energy expenditure (Park et al., 2021). Furthermore, the oxidative metabolism has been reported to range from 16-33% during a 30 s Wingate test (Kavanagh and Jacobs, 1988; Smith & Hill, 1991; O'Brien et al., 1997; Beneke et al., 2002). However, a shorter test duration demonstrates a reduction in the oxidative demand thus limiting the impact on the νLa_{max} (Langley et al., 2024).

Considering the oxidative contribution may enhance the accuracy of the νLa_{max} equation and provide insights into inter-individual differences in energy metabolism. Whilst the oxidative energy metabolism contribution to single sprint is small (Yang et al., 2023), events where repeated sprint performance is required, such as Olympic level sprint events enhance the reliance on the oxidative metabolism (Lievens et al., 2020).

Recently, Ferguson et al. (2021a) highlighted the linear relationship between power-outputs associated with high reliance on the oxidative metabolism (2-, 8- 20-min power) and 15 and 30 s sprint power. Subsequently, monitoring changes in the oxidative energy supply may highlight deficiencies and provide a basis for training recommendations to enhance sprint power (Ferguson et al., 2021a; 2021b; 2023). However, this approach requires an expensive metabolic cart and additional metabolic calculations to determine both the oxidative and PCr energy metabolism, making this approach practically challenging during field-based testing.

$$Pure\ \nu La_{max} = \frac{BLa_{maxpost} - BLa_{pre}}{t_{test} - (t_{alac} + t_{oxi})}$$

Equation (3)

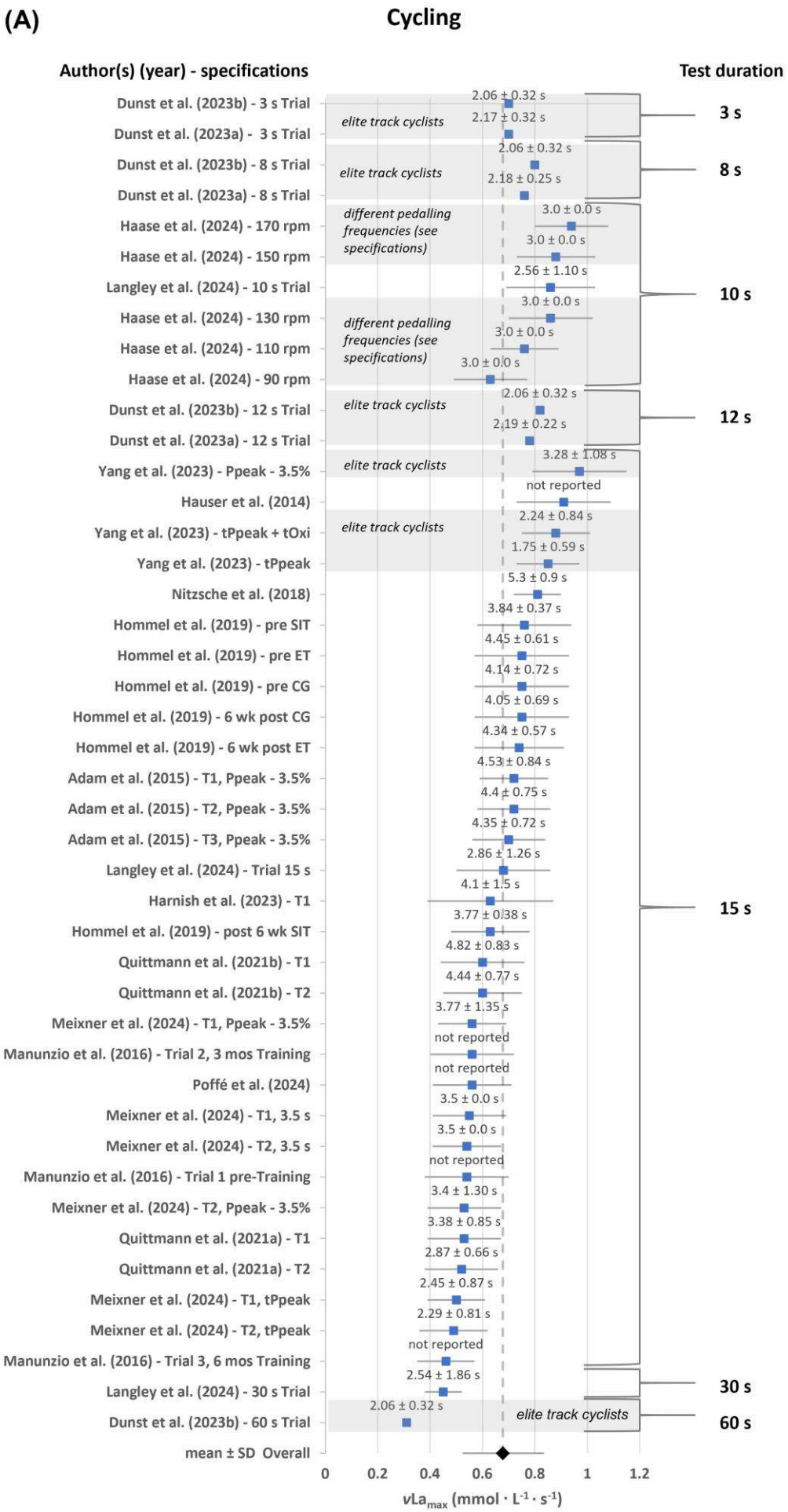
'Pure' νLa_{max} (mmol · L^{-1} · s^{-1}), t_{oxi} denotes the percentage of oxidative energy contribution converted into time in seconds (Yang et al., 2023).

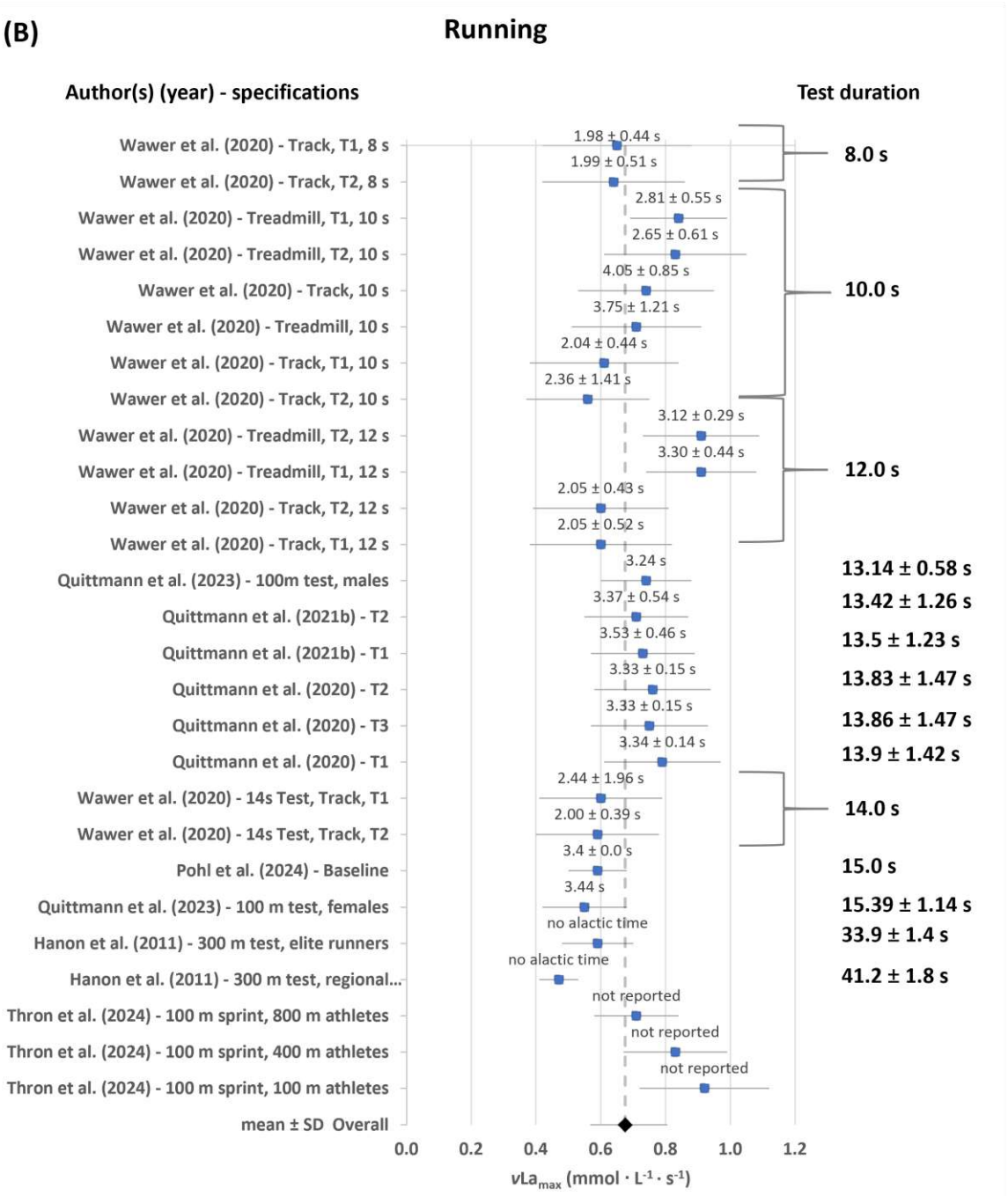
4.3 Test Duration

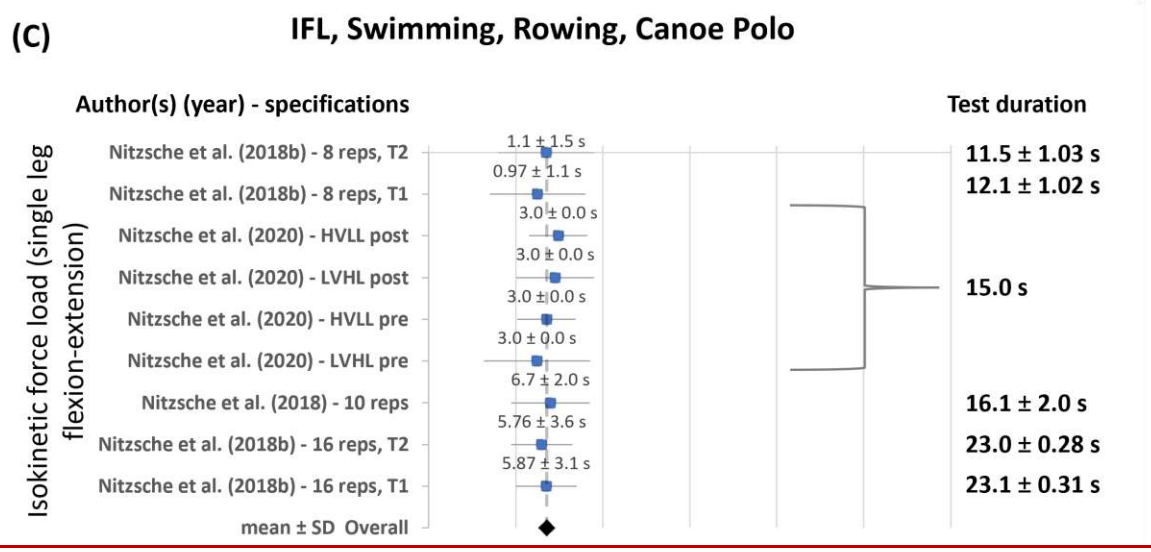
Along with the alactic time-period, the test duration comprises the denominator in the νLa_{max} equation and thus significantly influences the results (Mader, 1994). The optimal test duration should be sufficient in length to ensure the maximal rate of glycolytic flux is achieved, however, longer test durations may underestimate νLa_{max} for three key reasons: [1)] Glycolysis is self-limiting due to the production of H^+ causing a decline in muscle pH, which reduces the metabolic activity of PFK (Erecińska et al., 1995). [2)] The longer the test duration the larger the denominator, thus, the smaller the calculated νLa_{max}. [3)] Longer test durations may elicit pacing strategies, reducing the F-v and P-v profiles (Robin et al., 2021), and subsequent energy metabolism (Hirvonen et al., 1992). However, the shorter the test duration, the larger the influence of the alactic timespan. Where small variations in the alactic duration can lead to large fluctuations in the calculated νLa_{max} (Hauser, 2013). This is potentially problematic as this portion of the equation is subject to the largest error, reflected in the variance in the reliability (Table 2 and section 4.5).

Forest plots illustrated in Figure 5 demonstrate the influence of test duration, alactic time, performance level, and movement velocity on νLa_{max}. The mean νLa_{max} calculated from pooled data dependent on test duration grouped within 1 s identified the highest νLa_{max} was attained between test durations of 10 – 12 s for all modalities (cycling, running, swimming, and rowing) except isokinetic force tests (Figure 6 & 7). Figure 5A highlights both elite cyclists and high movement velocities produce high νLa_{max} values which may confound the results for cycling providing a bias to shorter test durations. Additionally, variations in the alactic times employed between studies makes interpretation of the influence of test duration challenging, as previously highlighted in Figure 3 longer alactic times are associated with a higher νLa_{max}.

Whilst data is more limited Figure 5C shows the shorter test durations ~10-12 s produced higher νLa_{max} values for both swimming and rowing. Contrary, mean νLa_{max} values varied by only 0.02 mmol · L^{-1} · s^{-1} for isokinetic force tests irrespective of test duration (~12 - 23 s). Longer relaxation phases of the knee flexors/extensors and small active muscle mass during isokinetic force testing may explain the small variance in νLa_{max} across test durations (Nitzsche et al., 2018b).


(A)
Cycling
Author(s) (year) - specifications
Test duration
Dunst et al. (2023b) - 3 s Trial
Dunst et al. (2023a) - 3 s Trial
elite track cyclists
2.06 ± 0.32 s
2.17 ± 0.32 s
3 s
Dunst et al. (2023b) - 8 s Trial
Dunst et al. (2023a) - 8 s Trial
elite track cyclists
2.06 ± 0.32 s
2.18 ± 0.25 s
8 s
Haase et al. (2024) - 170 rpm
Haase et al. (2024) - 150 rpm
Langley et al. (2024) - 10 s Trial
Haase et al. (2024) - 130 rpm
Haase et al. (2024) - 110 rpm
Haase et al. (2024) - 90 rpm
different pedalling frequencies (see specifications)
3.0 ± 0.0 s
3.0 ± 0.0 s
2.56 ± 1.10 s
3.0 ± 0.0 s
3.0 ± 0.0 s
3.0 ± 0.0 s
10 s
Dunst et al. (2023b) - 12 s Trial
Dunst et al. (2023a) - 12 s Trial
elite track cyclists
2.06 ± 0.32 s
2.19 ± 0.22 s
12 s
Yang et al. (2023) - Ppeak - 3.5%
elite track cyclists
3.28 ± 1.08 s
Hauser et al. (2014)
not reported
Yang et al. (2023) - tPpeak + tOxi
Yang et al. (2023) - tPpeak
elite track cyclists
2.24 ± 0.84 s
1.75 ± 0.59 s
Nitzsche et al. (2018)
5.3 ± 0.9 s
Hommel et al. (2019) - pre SIT
3.84 ± 0.37 s
Hommel et al. (2019) - pre ET
4.45 ± 0.61 s
Hommel et al. (2019) - pre CG
4.14 ± 0.72 s
Hommel et al. (2019) - 6 wk post CG
4.05 ± 0.69 s
Hommel et al. (2019) - 6 wk post ET
4.34 ± 0.57 s
Adam et al. (2015) - T1, Ppeak - 3.5%
4.53 ± 0.84 s
Adam et al. (2015) - T2, Ppeak - 3.5%
4.4 ± 0.75 s
Adam et al. (2015) - T3, Ppeak - 3.5%
4.35 ± 0.72 s
Langley et al. (2024) - Trial 15 s
2.86 ± 1.26 s
Harnish et al. (2023) - T1
4.1 ± 1.5 s
Hommel et al. (2019) - post 6 wk SIT
3.77 ± 0.38 s
Quittmann et al. (2021b) - T1
4.82 ± 0.83 s
Quittmann et al. (2021b) - T2
4.44 ± 0.77 s
Meixner et al. (2024) - T1, Ppeak - 3.5%
3.77 ± 1.35 s
Manunzio et al. (2016) - Trial 2, 3 mos Training
not reported
Poffé et al. (2024)
not reported
Meixner et al. (2024) - T1, 3.5 s
3.5 ± 0.0 s
Meixner et al. (2024) - T2, 3.5 s
3.5 ± 0.0 s
Manunzio et al. (2016) - Trial 1 pre-Training
not reported
Meixner et al. (2024) - T2, Ppeak - 3.5%
3.4 ± 1.30 s
Quittmann et al. (2021a) - T1
3.38 ± 0.85 s
Quittmann et al. (2021a) - T2
2.87 ± 0.66 s
Meixner et al. (2024) - T1, tPpeak
2.45 ± 0.87 s
Meixner et al. (2024) - T2, tPpeak
2.29 ± 0.81 s
Manunzio et al. (2016) - Trial 3, 6 mos Training
not reported
Langley et al. (2024) - 30 s Trial
2.54 ± 1.86 s
15 s
30 s
Dunst et al. (2023b) - 60 s Trial
2.06 ± 0.32 s
elite track cyclists
60 s
mean ± SD Overall
0
0.2
0.4
0.6
0.8
1
1.2
vLa_max (mmol · L⁻¹ · s⁻¹)


(B)
Running
Author(s) (year) - specifications
Test duration
Wawer et al. (2020) - Track, T1, 8 s
Wawer et al. (2020) - Track, T2, 8 s
Wawer et al. (2020) - Treadmill, T1, 10 s
Wawer et al. (2020) - Treadmill, T2, 10 s
Wawer et al. (2020) - Track, 10 s
Wawer et al. (2020) - Treadmill, 10 s
Wawer et al. (2020) - Track, T1, 10 s
Wawer et al. (2020) - Track, T2, 10 s
Wawer et al. (2020) - Treadmill, T2, 12 s
Wawer et al. (2020) - Treadmill, T1, 12 s
Wawer et al. (2020) - Track, T2, 12 s
Wawer et al. (2020) - Track, T1, 12 s
Quittmann et al. (2023) - 100m test, males
Quittmann et al. (2021b) - T2
Quittmann et al. (2021b) - T1
Quittmann et al. (2020) - T2
Quittmann et al. (2020) - T3
Quittmann et al. (2020) - T1
Wawer et al. (2020) - 14s Test, Track, T1
Wawer et al. (2020) - 14s Test, Track, T2
Pohl et al. (2024) - Baseline
Quittmann et al. (2023) - 100 m test, females
Hanon et al. (2011) - 300 m test, elite runners
Hanon et al. (2011) - 300 m test, regional...
Thron et al. (2024) - 100 m sprint, 800 m athletes
Thron et al. (2024) - 100 m sprint, 400 m athletes
Thron et al. (2024) - 100 m sprint, 100 m athletes
mean ± SD Overall
1.98 ± 0.44 s
1.99 ± 0.51 s
2.81 ± 0.55 s
2.65 ± 0.61 s
4.05 ± 0.85 s
3.75 ± 1.21 s
2.04 ± 0.44 s
2.36 ± 1.41 s
3.12 ± 0.29 s
3.30 ± 0.44 s
2.05 ± 0.43 s
2.05 ± 0.52 s
3.24 s
3.37 ± 0.54 s
3.53 ± 0.46 s
3.33 ± 0.15 s
3.33 ± 0.15 s
3.34 ± 0.14 s
2.44 ± 1.96 s
2.00 ± 0.39 s
3.4 ± 0.0 s
3.44 s
no alactic time
no alactic time
not reported
not reported
not reported
8.0 s
10.0 s
12.0 s
13.14 ± 0.58 s
13.42 ± 1.26 s
13.5 ± 1.23 s
13.83 ± 1.47 s
13.86 ± 1.47 s
13.9 ± 1.42 s
14.0 s
15.0 s
15.39 ± 1.14 s
33.9 ± 1.4 s
41.2 ± 1.8 s
0.0
0.2
0.4
0.6
0.8
1.0
1.2
vLa_max (mmol · L-1 · s-1)


(C)
IFL, Swimming, Rowing, Canoe Polo
Author(s) (year) - specifications
Test duration
Isokinetic force load (single leg flexion-extension)
Nitzsche et al. (2018b) - 8 reps, T2
Nitzsche et al. (2018b) - 8 reps, T1
Nitzsche et al. (2020) - HVLL post
Nitzsche et al. (2020) - LVHL post
Nitzsche et al. (2020) - HVLL pre
Nitzsche et al. (2020) - LVHL pre
Nitzsche et al. (2018) - 10 reps
Nitzsche et al. (2018b) - 16 reps, T2
Nitzsche et al. (2018b) - 16 reps, T1
mean ± SD Overall
1.1 ± 1.5 s
0.97 ± 1.1 s
3.0 ± 0.0 s
3.0 ± 0.0 s
3.0 ± 0.0 s
3.0 ± 0.0 s
6.7 ± 2.0 s
5.76 ± 3.6 s
5.87 ± 3.1 s
11.5 ± 1.03 s
12.1 ± 1.02 s
15.0 s
16.1 ± 2.0 s
23.0 ± 0.28 s
23.1 ± 0.31 s

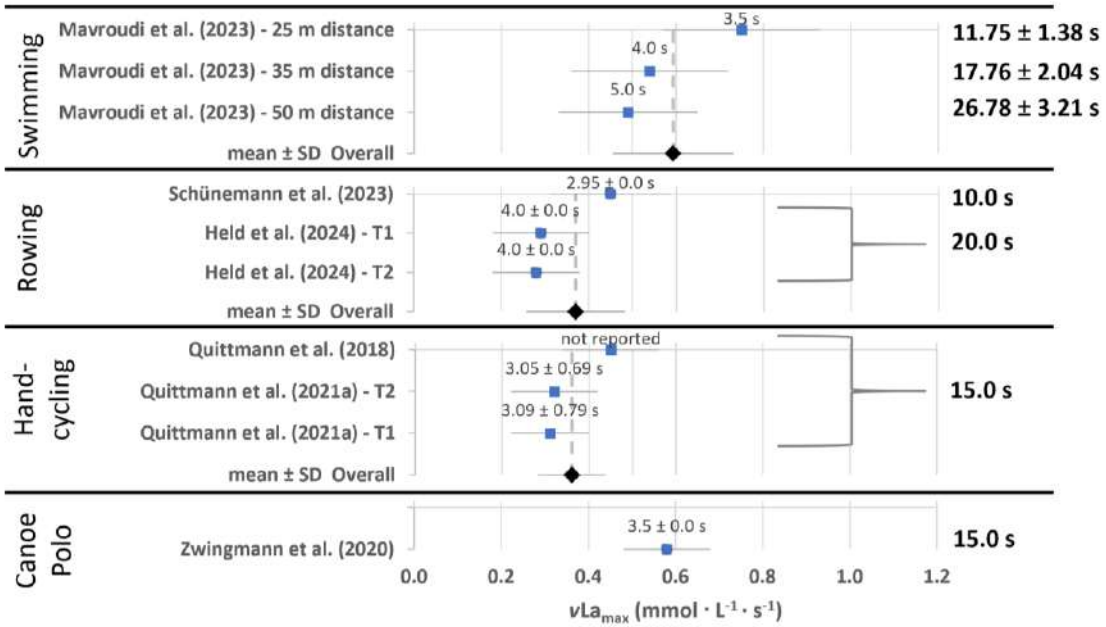


Figure 5. Three forest plots illustrate the reported νLamax results arranged dependent upon test duration and exercise modality (A) cycling, (B) running, and (C) various modalities including: isokinetic force load (IFL), swimming, rowing, hand-cycling, and canoe polo. Blue squares denote the group mean and standard deviation (SD) highlighted with error bars. Mean and SD alactic times are reported directly above each group νLamax. Black diamonds denote the mean values for modality, error bars represent SD. Grey highlights identify possible cofounding factors including performance level and movement velocity.

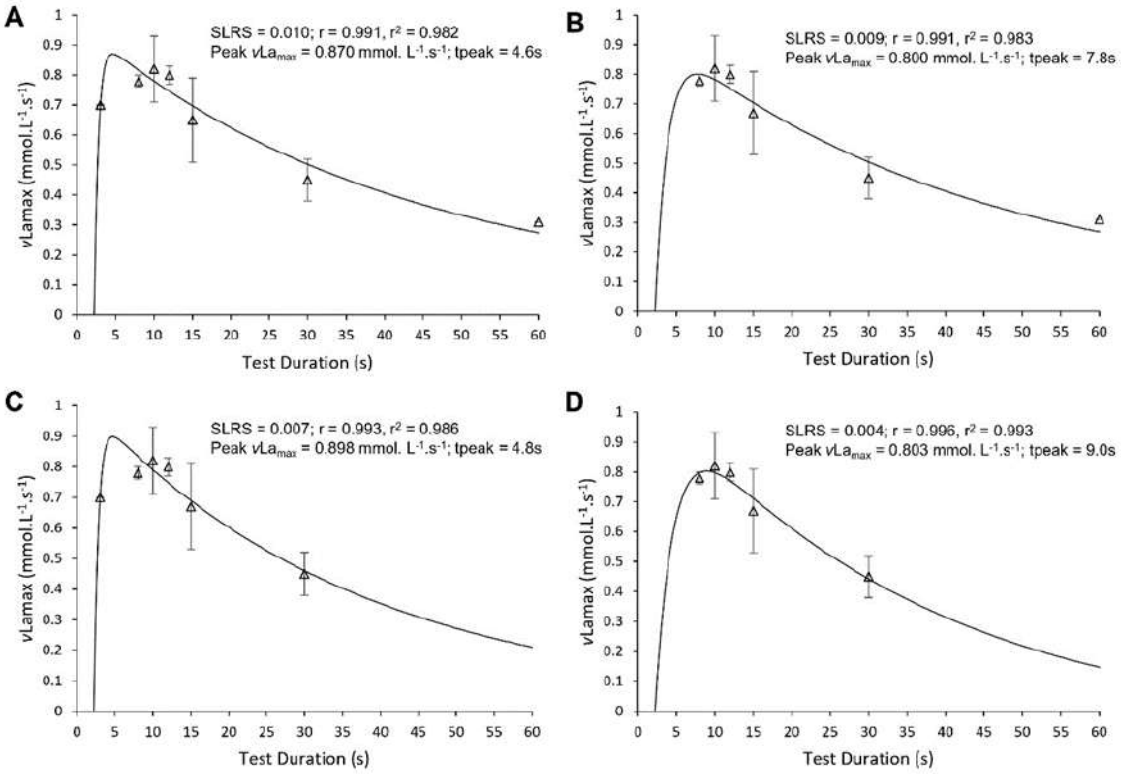


Figure 6. A four-panel plot illustrating data dependent bi-exponential models of cycling νLamax dependent on the test duration. Triangles denote the mean νLamax from pooled data, error bars represent the standard deviation, where there was a single study for the test duration raw standard deviation was applied. The alactic time component was constant at 2.12 s for all models in accordance with Dunst et al. (2023a; 2023b). **A)** Bi-exponential model calculated from the sum of least residuals squared (SLRS) using all data points. **B)** Bi-exponential model excluding 3 s test duration νLamax. **C)** Bi-exponential model excluding 60 s test duration νLamax. **D)** Bi-exponential model excluding both the 3 s and 60 s test duration νLamax. * νLamax from Dunst (2023a) and Dunst (2023b) have been calculated from their mean time of the fatigue-free force-velocity profile representing the alactic time-period, mean ΔBLC, and specific test duration.

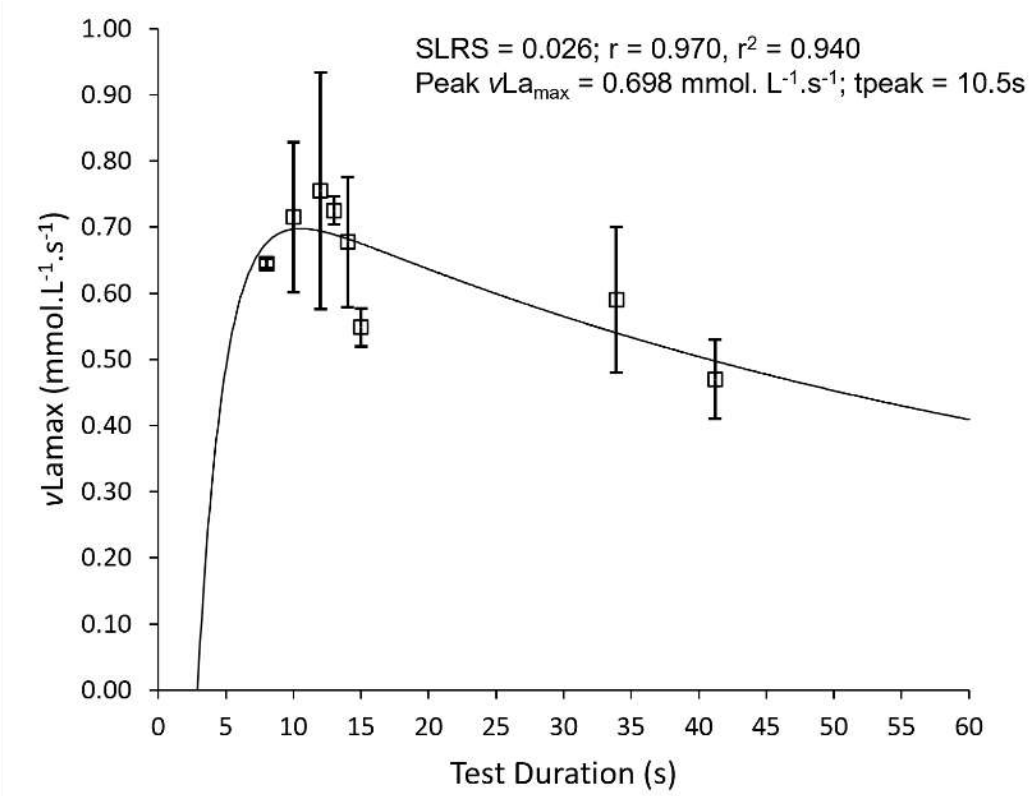


Figure 7. Running νLa_{max} bi-exponential model plotted against test duration. A mean alactic time of 2.9s was calculated from the mean values pooled and applied to the bi-exponential model.

The measurement of νLa_{max} at specific time points only allows comparisons to be drawn at each specific test duration. Individual data points do not reflect the νLa_{max} across all possible time points. To allow estimations of the νLa_{max} across all possible test durations bi-exponential models have been constructed using the pooled data for cycling (Figure 6) and running (Figure 7). Bi-exponential modelling predicts a test duration of 10.5 s as optimal to elicit the highest attainable νLa_{max} during running (Figure 7). Four separate bi-exponential models have been constructed for cycling with the exclusion of the data points for 3 and 60 s (Figure 6). All bi-exponential models demonstrate excellent fit ($r^2 \geq 0.982$) and predict the optimal test duration to elicit the highest νLa_{max} ranges from 4.6 – 9.0 s (Figure 6). Whilst model D predicting peak νLa_{max} to occur after 9.0 s offers the best fit ($r^2 = 0.993$) this is likely due to the inclusion of fewer data points. Models C and D exclude the 60 s test data point as this is beyond the recommended maximum test duration of 30 s (Heck et al., 2003). This inclusion may elucidate more accurate blood lactate kinetics. Models B and D exclude the 3 s data point where νLa_{max} is constructed from a small mean ΔBLC 0.62 mmol · L^{-1}, very short time denominator of 0.88 s and elite cohort (Dunst et al., 2023a; 2023b). Subsequently, minor changes will significantly influence the calculated νLa_{max}. Nevertheless, maximal glycolytic rate may occur earlier than previously predicted for testing νLa_{max} with Dunst et al. (2023a) demonstrating a nearly linear rate of lactate accumulation in the blood between 3, 8, and 12 s sprints. These findings are supported by Hirvonen et al. (1987) who observed a linear ΔBLC during sprint running over distances from 40-100 m.

As the νLa_{max} is dependent upon the test duration (Langley et al., 2024), a single test only corresponds to a single time point. With this consideration practitioners and researchers must ensure a standardised test duration to allow reliable comparisons. Furthermore,

without knowing the test duration for the individual which elicits the highest possible νLa_{max} a denotation of νLa_{peak} maybe more appropriate.

Furthermore, whilst utilising the νLa_{max} and $\dot{V}O_{2max}$ as input parameters within Mader's model of human energy metabolism (1984; Mader and Heck, 1986; Mader, 2003) provides a time efficient estimate an athletes MLSS (Quittmann et al., 2020), figures 6 and 7 highlight the potential perils of deriving the νLa_{max} from an inappropriate test duration. For example, determining the νLa_{max} from a test duration which is too long will underestimate the maximal glycolytic rate leading to higher calculated MLSS (Mader & Heck, 1986; Hauser et al., 2014; Wackerhage et al., 2023). Subsequently, the calculated MLSS will be above the athlete's physiological maximal metabolic steady state, pushing the athlete into the unsustainable severe exercise domain (Burnley & Jones, 2018). Additionally, underestimating the νLa_{max} may lead to inappropriate training recommendations to enhance the athletes MLSS based on metabolic profiles (Quittmann et al., 2020; Wackerhage et al., 2023).

4.4 The Influence of Modality, Whole, Upper, and Lower Body Exercise on νLa_{max}

Distinct differences in the amplitude of νLa_{max} are observed dependent upon the exercise modality irrespective of test duration (Figure 5). Key factors influencing νLa_{max} include; total work completed (Quittmann et al., 2020), quantity of active muscle mass (Medbø & Toska, 2001; Quittmann et al., 2020; Quittmann et al., 2021b), intra-individual fibre type distribution between muscles (Johnson et al., 1973; Tesch et al., 1978), lactate distribution volume (Medbø & Toska, 2001), sport specific motor recruitment patterns (Quittmann et al., 2020; Quittmann et al., 2021b), and the participants modality specific training background (Held et al., 2024).

The amplitude of νLa_{max} has been demonstrated to be higher, with more work achieved for a given duration, and associated with the amount of active muscle mass (Quittmann et al., 2020). The greater the active muscle mass results in an increased νLa_{max}, when comparing exercise modalities utilising upper or lower body extremities in isolation (Figure 5; Quittmann et al., 2020; Quittmann et al., 2021b). Whilst our results illustrate the highest νLa_{max} amplitude following cycling (Figure 5), Quittmann et al. (2021b) observed running elicits a higher νLa_{max} compared with cycling in the same cohort of participants. Differences may be observed due to elite sprint cyclist populations who possess large quantities of muscle mass around the quadriceps and hamstrings along with greater muscle pennation angles (Kordi et al., 2019) in comparison to endurance trained triathletes utilised by Quittmann et al. (2021b). Running may elicit higher νLa_{max} in participants of the same cohort due to greater activation of knee flexors and hip extensors, compared with cycling, due to an increase in active muscle mass (Jönhagen et al., 1996; Dorel et al. 2012). Additionally, whilst Quittmann et al. (2020) controlled the cycling frequency at 130 rpm, during sprint running stride frequency can exceed 250 steps per minute (Morin et al., 2011) with a higher movement velocity associated with higher νLa_{max} values (Haase et al., 2024).

Over a 15s test duration νLa_{max} values for upper or lower body modalities correspond with the amount of active muscle mass; cycling ~ 25% body mass (Medbø & Toska, 2001), Kayak estimated higher than hand cycling (Forbes & Chilibeck, 2007), hand cycling ~ 6.5% body mass (estimated from Quittmann et al., 2021a), Knee extensor isokinetic force ~ 4% body mass (Bangsbo et al., 1990). Whilst the upper extremities have a higher percentage of fast-twitch muscle fibres compared to the lower (Johnson et al., 1973), higher muscle

cross sectional area and lean segmental mass of the lower body (Quittmann et al., 2021b) appear more influential in νLa_{max} amplitude.

Intuitively whole-body exercise engaging larger volumes of muscle mass might be expected to elicit the highest νLa_{max} amplitudes. However, during whole-body exercise the influence of the active muscle mass appears to be masked (Figure 5; Table 1). Low νLa_{max} values observed in rowing maybe due to lower movement frequencies (Held et al., 2024). In rowing stroke rate peaks at ~50 strokes per minute (Held et al., 2024), in comparison to running, cycling, and handcycling νLa_{max} tests are conducted at considerably higher movement frequencies >100 steps or rotations per minute. Haase et al. (2024) recently reported higher movement frequencies within cycling elicit higher νLa_{max} amplitudes. This point has been supported by the recommendation Henneman's hierarchical size principle should incorporate movement velocity, with faster muscle fibre types being recruited with rising intensity and velocity (Dunst et al., 2024). Whilst the amplitude of νLa_{max} was higher for swimming comparable to cycling and running for the same test duration, a higher νLa_{max} was not attained despite the utilisation of larger quantities of muscle mass (Figure 5, Table 1). These values may also be observed due to slower movement frequencies, with the mean stroke rate within the 50m freestyle for males (59.58 ± 5.40 cycles·min^{-1}) and females (56.92 ± 3.24 cycles·min^{-1}) reported by Pelayo et al. (1996). The findings from this systematic review suggest an augmented demand on anaerobic glycolysis and/or reduced lactate clearance with faster movement frequencies.

Lactate uptake of the upper extremities has been shown to be negligible during cycling (Medbø & Toska, 2001). During whole body exercise, despite high rates of lactate appearance, arterial blood lactate concentrations can be maintained, due to the large capacity of active skeletal muscle to consume lactate (van Hall et al., 2003). Furthermore, higher lactate uptake compared to release from the legs was shown to be, the primary factor for maintaining low arterial BLC (van Hall et al., 2003). Van Hall et al. (2003) demonstrated that only active skeletal muscle consumes large quantities of lactate during exercise, due to enhanced energy expenditure, and correlated with enhanced muscle blood flow. The exercise modality may influence the lactate volume distribution during and post exercise dependent upon changes in blood flow redistribution (Medbø & Toska, 2001). For example, Quittmann et al. (2021b) observed a higher lactate removal velocity following handcycling compared with cycling. This is potentially due to venous-arterial lactate differences being greater following upper vs lower body exercise (Klausen et al., 1974). Higher lactate uptake of the legs (van Hall et al., 2003), coupled with changes in lactate distribution volumes (Medbø & Toska, 2001), may explain why smaller amplitudes in νLa_{max} are attained following whole-body vs lower body exercise.

In summary, distinct differences are observed in the peak amplitude of νLa_{max} between exercise modalities. These findings coupled with Quittmann et al. (2020; 2021a) highlight comparisons between νLa_{max} modalities should not be drawn. Large inter-individual differences, and low correlations between modalities (Quittmann et al. 2020; 2021a) demonstrate νLa_{max} is modality specific, sensitive to training history, movement velocity, and extremity specific. Therefore, testing the νLa_{max} should be specific to the sport modality (Held et al., 2024; Quittmann et al. 2020; 2021a).

4.5 νLa_{max} Reliability

Reliability studies focusing on test duration currently make it difficult to assess the stability of the νLa_{max} determination in the test-retest design. The available studies show moderate to excellent reliabilities based on correlation coefficients using a selected test duration. The test durations ranging from 8 to 23.1 ± 0.31 s (Table 2). Only Wawer et al. (2020) compared the reliability of the νLa_{max} across different test durations during running (non-motorized treadmill, running track), and found good to excellent reliabilities (ICC: 0.82 to 0.92). Lower correlation coefficients for test-retest trials were found by Nitzsche et al. (2018b) with isokinetic force loads. The coefficients were 0.72 at approximately 12 s and 0.48 at approximately 23 s, suggesting a lower reliability of the νLa_{max} with increasing test duration. The BLC prior to the test (BLC_{pre}) and the peak BLC (BLC_{peak}) are important in the calculation of νLa_{max} and thus, their reliability should be considered. In the studies included, correlation coefficients of the BLC_{pre} demonstrated a large range of 0.3 to 0.8 (Quittmann et al. 2021b; Adam et al. 2015) and coefficient of variation up to 45.6 % (Harnish et al. 2023; Adam et al. 2015), which indicates high variability or low stability.

A recent study by Pohl et al. (2024) indicates a reduced νLa_{max} with higher BLC_{pre}. The authors therefore suggest controlling BLC_{pre} more carefully with a $BLC_{pre} \leq 1.5$ mmol · L^{-1} following the warm-up. Research by Wittekind and Beneke (2011) also found reduced glycolytic rate with increased BLC_{pre} induced by a heavy warm-up. In this study a BLC_{pre} of 2.0 ± 0.3 mmol · L^{-1} did not significantly influence ΔBLC. Since in both studies the high-BLC_{pre}-condition were well above 1.5 and 2.0 mmol L^{-1} (3.37 ± 0.54 and 4.2 ± 0.9 mmol · L^{-1}), it is still unknown at which concentration ΔBLC is impaired. Irrespective of this, a light warm-up with a control of BLC_{pre} should be applied. A BLC_{pre} of ≤ 2.0 or ≤ 1.5 mmol · L^{-1} can be assumed to not influence the νLa_{max}. This could also help to reduce the variability and reliability of BLC_{pre}.

Furthermore, the correlation coefficients of the BLC_{peak} range from 0.69 to 0.91 (Nitzsche et al. 2018b; Adam et al. 2015; Quittmann et al. 2021b; Held et al. 2024; Wawer et al. 2020) with coefficient of variation from 5.2 to 23.3% (Adam et al. 2015; Harnish et al. 2023; Wawer et al. 2020) and indicate moderate to good reliability. Studies that reported correlation coefficients for ΔBLC reported values of 0.78 to 0.91 (Adam et al. 2015; Quittmann et al. 2021b; Meixner et al. 2024), which indicates good to excellent reliability. Although the reliability BLC_{pre} was lower than BLC_{peak}, this did not appear to affect the high stability of the ΔBLC.

The largest degree of error that most significantly influences the reliability of the νLa_{max} determination, is the alactic time span. Meixner et al. (2024), found that νLa_{max} calculated using different methods of t_{alac} determination, showed considerable differences in correlation coefficients. As shown in Table 2, the highest coefficients were calculated for fixed t_{alac} (3.5 s). The performance-dependent t_{alac} (TTP, TTP-3.5%) increase the standard error of measurement and coefficient of variance. Furthermore, Nitzsche et al. (2018b) showed decreasing correlation coefficients (<0.5) and increasing measurement errors for t_{alac} with increasing exercise time. The correlation coefficients of Wawer et al. (2020) appear to fluctuate unsystematically depending on the test duration (0.11-0.76). Only Adam et al. (2015) reports coefficients of performance-dependent t_{alac} (TTP-3.5%) greater than 0.8.

Lower reliability observed by Harnish et al. (2023) could stem from the use of a handheld blood lactate analyser (Lactate Plus) and an

unreported standardization of pedaling frequencies and load factor. The Lactate Plus samples a small quantity of blood (3-µl) and has been reported to produce a mean relative difference of –7% (2.5 to 97.5% percentile ranges –23 to 10%) when compared with the Biosen (Mentzoni et al., 2024). To standardise movement velocity νLa_{max} tests are typically conducted in isokinetic mode (120, 130 rpm) on a cycle ergometer (Hauser et al., 2014, Adam et al., 2015, Quittmann et al., 2018, Quittmann et al., 2021a, Yang et al., 2023, Dunst et al., 2023a, b, Meixner et al., 2024, Poffé et al., 2024). Studies investigating the reliability of the νLa_{max} as a function of movement frequency (cadence, angular velocity) are still pending, but it can be assumed that the νLa_{max} is influenced by the movement velocity (Haase et al., 2024). The present reliability studies used only two repeated measurements (Harnish et al., 2023; Held et al. 2024; Meixner et al., 2024; Nitzsche et al., 2018b; Quittmann et al., 2021a; Quittmann et al., 2021b; Wawer et al., 2020) except Adam et al. (2015) who used three repeated trials.

Accurate comparisons in the reliability of νLa_{max} between different populations including sex and performance level cannot be drawn. Seven of the eight studies examining reliability included both male (n = 196) and female (n = 65) participants (n = 261) (Table 2). However, no study directly compared the reliability of the νLa_{max} or lactate kinetics between sexes. Whilst Harnish et al. (2023) observed no statistical differences in blood lactate parameters, alactic time, or νLa_{max} between sexes, several studies report sex differences between both lactate parameters and νLa_{max} (Adam et al., 2015; Held et al., 2024; Meixner et al., 2024b). Sex differences in the νLa_{max} are likely to occur, with females likely to express lower maximal glycolytic rates due to differences in lean body mass (Miller et al., 2024), lower activities of PFK, pyruvate kinase, lactate dehydrogenase, hexokinase, glycogenolysis phosphorylase, and succinic dehydrogenase (Green et al., 1984; Jaworowski et al., 2002). These findings suggest further exploration of sex differences are required. Due to the homogeneity of the participants performance level (Amateur/ University Students: n = 7; National Level: n = 1) comparisons in the test reliability cannot be drawn.

In summary, the current reliability of νLa_{max} ranges from moderate to excellent (Table 2). The reliability of the νLa_{max} can be enhanced by applying a fixed alactic timespan (Meixner et al. 2024), employing shorter test durations (Nitzsche et al., 2018b), standardising movement velocity where possible (Haase et al., 2024), and by controlling the BLC prior to the test within a narrow margin (Adam et al. 2015; Harnish et al. 2023; Pohl et al., 2024).

4.6 Training Interventions Influence on νLa_{max}

It is assumed that a high νLa_{max} is unfavorable in endurance disciplines. A higher νLa_{max} with a constant $\dot{V}O_{2max}$ leads to a reduction in performance at the MLSS (Wackerhage et al., 2022). This is evident, in lower νLa_{max} values of 800 m runners compared to 100 m sprinters (Thron et al., 2024). In contrast, a high νLa_{max} is necessary for sprint disciplines (Wackerhage et al., 2022). It seems apparent that highly endurance trained athletes have a lower νLa_{max} compared to anaerobically trained athletes such as track cyclists (e.g. results from Yang et al. (2023) vs. Quittmann et al. (2021a)). At what point the νLa_{max} is low or high is difficult to assess due to the methodological differences in the determination. In addition, the νLa_{max} and its adaptation should be considered in combination with changes in $\dot{V}O_{2max}$ and always with a view to the desired performance. Olbrecht and Mader (2005) describe improvements of the performance (e.g., shift of

a lactate curve) can be the results of different combinations and adaptations of νLa_{max} (↑→↓) and $\dot{V}O_{2max}$ (↑→↓). In line with this, Hauser et al. (2014) could show that the achieved power at the MLSS can almost be identical, but resultant from different combinations of νLa_{max} and $\dot{V}O_{2max}$. It is hypothesised that endurance training leads to a reduction in νLa_{max}, however, training intervention studies on the νLa_{max} are scarce. Where, only two studies met our inclusion criteria (Hommel et al., 2019; Nitzsche et al., 2020).

Endurance training methods, such as moderate intensity continuous training or high intensity interval training typically result in an increase of $\dot{V}O_{2max}$ (Poon et al., 2021), probably accompanied by a reduction of νLa_{max} or no change of νLa_{max} (Mader & Heck, 1986; Wackerhage et al., 2022). This hypothesis is supported by Hommel et al. (2019) who observed a significant reduction in νLa_{max} and an increase in $\dot{V}O_{2max}$ following 6-weeks of sprint interval training (30 – 40 mins with 4 – 6 Wingate tests lasting 30 s each) in physical education students, who were not specifically trained in endurance or sprinting. High volume training (60 min at 1.5 to 2.5 mmol · L^{-1} BLC), on the other hand, increased $\dot{V}O_{2max}$ but did not significantly alter νLa_{max} (Hommel et al., 2019). However, the training interventions lacked standardisation of the intensity of both the sprint interval and high-volume training. Contrary, resistance training over 6-weeks resulted in an increase of νLa_{max} regardless of intensity or training volume (Nitzsche et al., 2020). Furthermore, Sperlich et al. (2010) observed a significant increase of νLa_{max} following 5-weeks of HIIT and a decrease following 5-weeks of high-volume training in swimming, contrary to Hommel et al. (2019). However, the νLa_{max} test duration was ~85 s, well above the recommended test duration, and it is questionable whether the adaptation of the νLa_{max} will be similar with a shorter test duration. An observational study by Manunzio et al. (2016) was conducted over six months prior to an ultra-endurance race. $\dot{V}O_{2max}$ increased moderately and νLa_{max} decreased significantly associated with an increased training volume around the MLSS and above, while the volume of low intensity training was reduced. The studies by Sperlich et al. (2010) and Manunzio et al. (2016) are both worth mentioning. However, both studies were excluded from the systematic review due to methodological limitations (test duration ~85 s) or due to the observational character of the study.

Data available does not allow any clear conclusions to be drawn. It is also unclear how the training status affects the adaptation of the νLa_{max}. Further training studies are required in which intensity and volume are varied in small steps and the adaptations of νLa_{max} and $\dot{V}O_{2max}$ should be monitored carefully. Standardised methodologies for testing the νLa_{max} needs to be agreed and applied to allow accurate comparisons to be drawn (See 4.8. for more details).

4.7 Blood Lactate Sampling

The most common blood lactate sampling method was sampling every minute for 10-minutes post exercise for a total of 11 post exercise samples (Table 1). This was used in 17 of the 27 articles, with three other articles using a similar methodology with additional samples. Exercise duration has a significant role in $tBLC_{max}$ whereby shorter tests durations lend themselves to a reduced $tBLC_{max}$. Langley et al. (2024) demonstrated $tBLC_{max}$ peaked between 5 ± 2 min, 6 ± 2 mins, and 7 ± 2 mins following 10, 15, and 30 s cycling durations. Mavroudi et al. (2023) also reported that the shorter the swimming distance the quicker the $tBLC_{max}$ in 25, 35, and 50 m swimming sprints, respectively. Therefore, the consensus should not be limited to a specific sampling duration post exercise, but be reflective of the environment the test is conducted in. If a νLa_{max}

is conducted in the field with applied practitioners, post exercise samples should be taken every minute (including immediately post exercise) until BLC_{max} values are identified minus 1 mmol · L^{-1}. This will certify a true BLC_{max} is detected whilst minimising the amount of post exercise samples. This maintains the integrity of the test whilst reducing the burden on the practitioner and the athlete.

In order to increase the accuracy of the BLC_{max} determination and enforce strict scientific rigor, post exercise samples could be taken every 30 s (including immediately post exercise) until peak blood lactate values are identified minus 1 mmol·L^{-1}. It could be argued this frequency of sampling would further improve accuracy. However, a study by Nitzsche & Haase (2023) showed no significant differences in the determination of BLC_{max} using a bi-exponential function, with a blood sampling rate every 30 s compared to every 60 s up to the 9th minute following a maximal sprint. The use of a bi-exponential function also offers the advantage of determining lactate kinetics (lactate invasion and elimination) more precisely. This is a growing interest in νLa_{max} research but requires a longer post exercise measurement period (up to 30 minutes), thus more blood samples, whereby the frequency of the blood samples is reduced after the BLC_{max} occurs (Beneke et al., 2010). Further, reporting $tBLC_{max}$ in future νLa_{max} research will better inform the readers of the post exercise lactate kinetics across different modalities and populations.

Following the sprint, the athlete should remain inactive to not influence the BLC, as active recovery is known to increase the lactate elimination out of the blood compartment for example following multiple sprints (Kappenstein et al., 2015) and following a maximal incremental test (Taoutaou et al., 1996). BLC_{peak} was not influenced in these studies. However, it is currently unknown how active recovery affects the BLC after a single sprint, and a reduced BLC_{peak} would result in reduced ΔBLC and νLa_{max}. Researchers should clearly indicate whether their athletes/participants are active or passive after the sprint test.

4.8 Test Recommendations

4.8.1 General Test Recommendations

To allow accurate, reliable, and valid νLa_{max} test results the protocol needs to be standardised specific to the test scenario and modality. To gain an accurate assessment during maximal performance tests the athlete should be familiarised with the test protocol (Ozkaya, 2013) and highly motivated to attain maximal effort (Rendos et al., 2019). Additionally, factors including baseline blood lactate concentration, and prior carbohydrate ingestion (Pohl et al., 2024) need to be considered to allow accurate and reliable results. Therefore, several general test recommendations should be implemented:

1) Baseline blood lactate should be < 1.5 mmol · L^{-1} (Pohl et al., 2024).
2) Participants should consume a carbohydrate rich diet of >6g·kg body mass per day for 48-72 hours prior and avoid long and vigorous exercise 48-hours prior to ensure the participants attend in a glycogen rich state (Hawley et al., 1997).
3) Avoid consumption of any glucose containing beverages (e.g., juice, soft drinks) or energy gels in the hour prior to νLa_{max} testing (Pohl et al., 2024).
4) Abstinence of caffeine (in any form) 6 - 12 hours prior. This recommendation stems from the potential influence of caffeine on the test results. Caffeine has been shown to increase the mean and peak power in a Wingate test (Grgic, 2018) and to increase the

BLC in submaximal exercise (Glaister & Gissane, 2018). Therefore, Glaister and Gissane (2018) emphasise the importance of caffeine withdrawal before any experimental intervention. However, withdrawal from caffeine can result in symptoms like headaches, tiredness/fatigue or decreased energy/activeness (Juliano & Griffiths, 2004), which may add a confounding variable (Merrell et al., 2024). The half-life of caffeine is generally 4 – 6 h but varies between 2 h to 10 h (Blanchard & Sawers, 1983; Guest et al., 2021) and caffeine withdrawal symptoms emerge after 12-24 h (Juliano & Griffiths, 2004). If caffeine abstinence is not possible, the participants are encouraged to document caffeine consumption and replicate consumption prior to all trials. This is particularly important for repeated measurements (e.g., in reliability or training studies).

5) Arrive in euhydrated state due to dehydration causing higher BLC during exercise (Green et al., 2018; Logan-Sprenger et al., 2013). To ensure adequate hydration it is recommended to consume a minimum of 40 mL·kg body mass of water the day prior (Vivanti, 2020).
6) Participants should complete at least one all-out familarisation trial prior (Ozkaya, 2013).
7) Loud verbal encouragement should be provided throughout test procedures (Rendos et al., 2019).
8) νLa$_{max}$ test duration should be between 8 – 12 s irrespective of modality (Figure 5). Activities which are more conducive to assessment over a given distance e.g., running and swimming would benefit from aiming for a task completion time within this range.
9) A passive seated rest period following the test during blood lactate sampling to minimise removal of lactate from the blood for metabolism.

4.8.2 νLa$_{max}$ Test Recommendations & Considerations

Currently, the body of research demonstrates an overwhelming lack of consensus to testing the νLa$_{max}$. A standardised test protocol must be implemented between scientists and practitioners to enhance the reliability of the results and allow for meaningful comparisons between data to be drawn. Table 4 outlines a standardised νLa$_{max}$ test protocol we advocate to be implemented between researchers and practitioners to provide continuity in measures derived from the results of this review.

Table 4. Recommendations for a standardised νLamax Test Protocol.

Time	Component	Recommended procedure
Pre-Test	Nutritional Status	Glycogen rich state and Euhydrated: > 6g · kg body mass of CHO and 40 mL·kg body mass of water the day prior.
	Baseline blood lactate	< 1.5 mmol · L^{-1}
Test	Test Duration	10 s
	Alactic Time	3 s
	Movement Velocity	Isokinetic mode (where applicable): Cycling cadence 130 rpm.
	Encouragement	Loud vocal encouragement throughout.
Post-Test	Recovery	Seated passive recovery
	Blood lactate sampling	BLC sampled from the earlobe every 60 s until BLC$_{peak}$ minus 1 mmol · L^{-1}.
	Identification of BLC$_{peak}$	Highest measured BLC.
	νLa$_{max}$ formula	$vLa_{max} \frac{BLa_{\max post} - BLa_{pre}}{t_{test} - t_{alac}}$

Scientific research aiming to derive mechanistic understanding of energy metabolism are encouraged to adopt Yang et al. (2023) 'pure νLa_{max}' formula to deduce the oxidative contribution from the test time. This method requires a metabolic cart to measure $\dot{V}O_2$ before, during, and after, the νLa_{max} test protocol to allow energy contributions to be derived from PCr-La^{-}-O_2 energy equivalence (Yang et al., 2023). Whilst this approach provides valuable insight into the athletes underpinning metabolism, adoption of this procedure has been omitted from our recommendations due to the requirements of an expensive metabolic cart and additional mathematical procedures which complicated test procedures. Furthermore, the influence of the oxidative metabolism on the νLa_{max} appears small when utilising a 10 s sprint (Langley et al., 2024; Langley & Porter, 2024).

If the researcher wishes to explore the mechanistic underpinnings of energy metabolism we advocate estimating the participants fat-free mass in accordance with Meixner et al. (2024). Estimation of the participants fat-free mass enhances the accuracy of determining the glycolytic energy contribution (Meixner et al., 2024b). The mechanical energy equivalent of 1 mmol $\cdot$ L^{-1} of blood lactate accumulation can be calculated as 12 J/kg of fat-free mass (Meixner et al., 2024b).

To derive the most accurate determination of BLC_{max} and subsequent νLa_{max} researchers should employ a bi-exponential function as detailed by Beneke et al. (2005) and Beneke et al. (2007). As described in section 4.7. bi-exponential modelling provides further insight into blood lactate kinetics including lactate invasion and elimination time parameters, this approach has been readily employed by several researchers to gain further understanding of the athlete physiological profile (Dunst et al., 2023a, 2023b; Haase et al., 2024; Quittmann et al., 2018, 2020, 2021a, 2021b). Whilst this approach offers the most accurate determination of the νLa_{max} differences between peak concentrations measures and modelled values are likely to be small and place additional time requirements for the participant. To employ ease of testing for both scientists and practitioners the use of bi-exponential modelling has not been suggested within the standardised recommendations.

4.8.3 Modality specific recommendations

During cycle ergometry the movement velocity has been demonstrated to significantly influence the νLa_{max} amplitude with higher pedalling frequencies stimulating higher νLa_{max} amplitudes (Haase et al., 2024). Subsequently, pedaling frequency needs to be controlled. We recommend the νLa_{max} test should be conducted in isokinetic mode at a pedalling cadence of ≥ 130 rpm in accordance with Haase et al. (2024). To reduce the loss of force transmission and engage the hamstring muscles in the upcycle of the pedal stroke participants should utilise clipless pedals where possible (Hintzy et al., 1999).

Currently, there is limited data to draw distinct sports specific νLa_{max} recommendations for other sporting modalities. Only one study in running has been conducted to test the reliability between non-motorised treadmill and track running (Wawer et al., 2020). Furthermore, within running no studies have evaluated the differences in νLa_{max} tested over a set duration and set distance. Set running distances make comparisons between individuals and studies challenging due to the time dependence of the νLa_{max} formula. Swimming stroke frequency is likely to influence νLa_{max} and therefore the νLa_{max} is likely to be stroke specific due to differences in movement frequencies between strokes (Hellard et al., 2008). During isokinetic

force testing the angular velocity influences the νLa_{max} with 210° · s^{-1} previously utilised as demonstrated to elicit the highest νLa_{max} (Nitzsche et al., 2018b).

4.9 Limitations

4.9.1 Limitations of Bi-exponential modelling to identify optimal test duration

Bi-exponential modelling time to peak νLa_{max} from pooled data is not without limitations. Firstly, this data combines data from both sexes, varying training status (recreational – elite), and athletes with different specialisms (sprint or endurance). νLa_{max} has been reported lower in females than their male counterparts (Harnish et al., 2023; Meixner et al., 2024b; Poffé et al., 2024, Thron et al., 2024) and inclusion of both sexes may lower the average peak νLa_{max}, skewing results when compared to all male counterparts. Studies investigating the νLa_{max} in elite level sprint cyclists (Dunst et al., 2023a, 2003b; Yang et al., 2023) report very high values, compared with elite endurance cyclists (Manunzio et al., 2016), and amateur cyclists (Harnish et al., 2023; Meixner et al., 2024b). Furthermore, two studies (Haase et al., 2024; Langley et al., 2024) investigating a 10 s test duration both utilised high pedaling cadences (90 – 170, 145 ± 7 rpm) which promote higher νLa_{max} results (Haase et al., 2024).

4.9.2 Standardisation of analysis of blood lactate accumulation kinetics

Limited studies (5) report the post exercise blood lactate kinetics including the time to peak or the rate of accumulation and rate of disappearance. Including post exercise blood lactate kinetics may allow for more accurate determination of when peak blood lactate occurs in varying populations and allows inferences of training status regarding lactate disappearance (Stallknecht et al., 1998). Furthermore, varying sampling times, frequencies, and duration of post exercise blood lactate kinetics make comparisons of νLa_{max} values challenging. Whilst some studies calculate νLa_{max} from measured BLC others utilise bi-exponential modelling of blood lactate to identify peak concentrations. These differences in methods may influence the derived νLa_{max} making comparisons between studies challenging.

4.9.3 Standardisation of analysis of blood lactate accumulation kinetics

Inferences have been made between and within modalities in this review, although it should be outlined that movement velocities within modality can lead to distinct changes in νLa_{max}. Movement velocities have been shown to be influential on lactate kinetics and energy availability (Gottshall et al., 1996, Gentil et al., 2006). Therefore, future research needs to consider how combining modalities via time under tension or speed of cyclical movement (rpm or cadence) may affect lactate kinetics thus νLa_{max}.

4.9.4 Demographic of participants

Due to the moderate number of cycling studies, inferences from both elite and amateur populations were amalgamated. Cycling specific considerations in this review has consciously taken ability level into account. Future research is needed in a variety of populations (amateur, well-trained, & elite) in each modality (cycling & running) to ensure population specific inferences can be made. Additionally, inferences between endurance and sprint trained individuals were also combined due to the limited number of studies. Both limitations (participation level and training characteristic) are minor but require future research before direct comparisons can be made.

4.9.5 *Limitations of the review process*

The moderate number of articles included into some categories of this systematic review limits our ability to draw firm conclusions about the modality (swimming, rowing, and kayak) and duration specific inferences during a νLa_{max} test. This further highlights the need for more studies of varying modalities and test durations in the νLa_{max} literature. The limited number of training intervention studies leads to reduced inferences regarding if the νLa_{max} is trainable and if so, what training interventions offer the best avenue to enhance or reduce the νLa_{max}. Additionally, it can be noted that even though this systematic review followed the PRISMA guidelines, it is conceivable that some articles could have been missed or incorrectly excluded during the screening process.

The maximum lactate accumulation rate could also have clinical relevance in the future. Various diseases that affect muscle metabolism and cause maladaptation's in energy supply show a muscle fiber shift because of these changes (COPD, heart failure, type II diabetes). The νLa_{max}/νLapeak could also be a significant factor in muscle diseases with genetically triggered enzyme defects that lead to faster exhaustion during physical activity due to disruption of muscle energy metabolism. Furthermore, it's possible the use the νLa_{max} can be used as a metabolic performance parameter to determine muscle adaptations following training interventions as a minimal invasive method, as shown in an initial study (Nitzsche et al., 2021).

4.10 Future Research Directions

Based on the current body of evidence the key priority is to standardise the νLa_{max} testing procedures within the scientific community and between practitioners. Therefore, we advocate for scientists and practitioners to embrace the recommended procedures including:

1) A standardised test duration of 10s.
2) A standardised alactic time interval of 3 s.
3) Baseline blood lactate values below 1.5 mmol · L^{-1}.
4) Post test blood lactate sampling every 60 s from the earlobe until a decline in 1 mmol · L^{-1} from peak blood lactate is observed.
5) Standard passive seated recovery post sprint.

This systematic review has highlighted numerous gaps in the νLa_{max} literature that need addressing to improve the rigor of the νLa_{max} principle. We recommend that future research focuses on the following areas:

1) Currently, there are no validation studies analysing the νLa_{max} measured from blood lactate and the *V*max of glycolysis. Therefore, validation studies are required to analyse the relationship between the maximal rate of glycolysis within the muscle and the νLa_{max} assessed at the whole-body level.
2) Identification of which method offers the highest validity and reliability to estimate the alactic time interval.
3) Establish normative data for the νLa_{max} for both male and female populations.
4) Further analysis of how different training interventions influences the interactions between νLa_{max}, $\dot{V}O_{2max}$, MLSS and subsequent influence on performance.
5) Analysis of what variables impact predictions of the maximal metabolic steady state when applying Mader's mathematical model of human energy metabolism (Mader, 1984) and what approaches identify the most accurate model to determine the MLSS.

5 Conclusions

This systematic review of twenty-seven experimental research articles, outlines the current methodological approaches, provides recommendations to optimise νLa_{max} procedures and future research. We also provide clarity that the νLa_{max} formula derived from blood lactate concentrations was initially proposed by Mader (1994), with earlier mathematical models of human energy metabolism (Mader, 1984; Mader and Heck, 1986) applying maximal lactate formation rate directly within the muscle cell.

Identification of the alactic time-period introduces the largest area of error within the reliability of the νLa_{max}. To minimise such error a fixed alactic timespan should be employed. The νLa_{max} is modality specific and movement velocity dependent, thus νLa_{max} should be tested specific to the sporting modality. Based on the results from this review we propose a standardised test procedure to be adopted by researchers and practitioners. Key test recommendations include: Pre-test blood lactate values < 1.5 mmol · L^{-1}, a test duration of 10 s, a fixed alactic timespan of 3 s, standardised movement velocity (where applicable), a passive recovery, and post exercise blood lactate sampling every minute until peak minus 1 mmol · L^{-1}.

Funding: RH receives a scholarship from the Sächsische Aufbaubank (SAB) with funds from the European Social Fund Plus (ESF Plus) and the Free State of Saxony.

Acknowledgments: The authors would like to acknowledge the work of authors of all the manuscripts included into the systematic review.

Conflicts of Interest: No conflicts of interest, financial or otherwise, are declared by the authors.

Author Contribution: All authors (JL, RH, NN & MP) contributed to the conception and design of the review, screening of articles, analysis of data and interpretation of results, and the construction of the manuscript from draft to final approved manuscript.

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