Is Maximal Lactate Accumulation Rate Promising for Improving 5000-m Prediction in Running?

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ABSTRACT

Endurance running performance can be predicted by maximal oxygen uptake ($\dot{V}O_2max$), the fractional utilisation of oxygen uptake ($\%\dot{V}O_2max$) and running economy at lactate threshold (RE_{OBLA}). This study aims to assess maximal lactate accumulation rate ($\dot{c}La_{max}$) in terms of improving running performance prediction in trained athletes. Forty-four competitive female and male runners/triathletes performed an incremental step test, a 100-m sprint test and a ramp test to determine their metabolic profile. Stepwise linear regression was used to predict 5000-m time trial performance. Split times were recorded every 200-m to examine the 'finishing kick'. Females had a slower t_{5k} and a lower $\dot{V}O_2max$, $\dot{c}La_{max}$, 'finishing kick' and RE_{OBLA}. Augmenting Joyner's model by means of $\dot{c}La_{max}$ explained an additional 4.4 % of variance in performance. When performing the same analysis exclusively for males, $\dot{c}La_{max}$ was not included. $\dot{c}La_{max}$ significantly correlated with $\%\dot{V}O_2max$ ($r = -0.439$, $p = 0.003$) and the 'finishing kick' ($r = 0.389$, $p = 0.010$). $\dot{c}La_{max}$ allows for significant (yet minor) improvements in 5000-m performance prediction in a mixed-sex group. This margin of improvement might differ in middle-distance events. Due to the relationship to the 'finishing kick', $\dot{c}La_{max}$ might be related to individual pacing strategies, which should be assessed in future research.

ABBREVIATIONS

ANOVA	Analysis of variance
ASR	anaerobic speed reserve (v_{100}-$\dot{V}O_2max$)
d	Cohen's d effect-size
$HR_{max,5k}$	maximal heart rate attained during the 5000-m time trial
$HR_{max,RT}$	maximal heart rate attained during the ramp test protocol
$HR_{max,ST}$	maximal heart rate attained during the incremental step test protocol
$HR_{mean,5k}$	mean heart rate attained during the 5000-m time trial
HR_{OBLA}	interpolated heart rate corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA)
$La_{max,ST}$	maximal lactate concentration attained during the incremental step test protocol

$La_{post,5k}$	lactate concentration immediately after performing the 5000-m time trial
$La_{post,RT}$	lactate concentration immediately after performing the ramp test protocol
p	probability of finding the observed (or more extreme) results when the null hypothesis is assumed to be true
r	correlation coefficient
R²	determination coefficient
RE_{12}	interpolated running economy at 12 km · h^{-1}
RE_{OBLA}	interpolated running economy corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA)
RER_{max}	maximal respiratory exchange ratio attained during the ramp test protocol
t_{100}	time to perform the 100-m all-out sprint
t_{5k}	time to perform the 5000-m time trial
TTE	time to reach subjective exhaustion during the ramp test protocol (excluding the time to perform the warm-up)
v_{100}	average speed in the 100-m all-out sprint (100/t_{100})

$v_{200}/v_{4.8k}$	ratio of the mean velocity during the final 200-m of the 5000-m time trial and the mean velocity attained during the prior 4800-m (‘finishing kick’)
$\dot{c}La_{max}$	maximal lactate accumulation rate
v_{OBLA}	interpolated velocity corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA)
$\dot{V}O_2max$	relative maximal oxygen uptake
$v\dot{V}O_2max$	minimal velocity necessary to elicit maximal oxygen uptake in the ramp test
$\%\dot{V}O_2max$	fractional utilization of $\dot{V}O_2max$ at lactate threshold according to a fixed lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA)
α	level of significance
ΔLa_{100}	maximal post-exercise increase in lactate concentration following the 100-m all-out sprint test
ΔLa_{RT}	increase in lactate concentration during the course of the ramp test protocol
ΔLa_{5k}	increase in lactate concentration during the course of the 5000-m time trial

Introduction

Knowledge about the determinants of endurance performance and the underlying metabolic profile is crucial for developing adequate exercise tests, provide concrete recommendations for improvement and individualise training prescriptions for athletes. Especially in the field of exercise physiology, various concepts have been developed to predict endurance performance by means of physiological parameters [1]. The most common model has been developed by Michael J. Joyner in 1991, who calculated running speed in the marathon by means of maximal oxygen uptake ($\dot{V}O_2max$), the fractional utilisation of oxygen uptake at lactate threshold ($\%\dot{V}O_2max$) and running economy (RE) [2]. Whereas the factors underlying $\dot{V}O_2max$ [3–5] and RE [6–8] have extensively been examined in previous research, the physiological origin of $\%\dot{V}O_2max$ (and the corresponding lactate threshold) remained mostly unknown. As an example, recent research indicated that the velocity and corresponding $\%\dot{V}O_2max$ at lactate threshold do not significantly correlate [9].

The goal of most lactate threshold concepts is to estimate the maximal lactate steady-state (MLSS), which is defined as the highest intensity at which lactate production and clearance are in equilibrium [10]. As one example, the intensity corresponding to a lactate concentration of 4 mmol · l^{-1} (v_{OBLA}) has demonstrated a high correlation and agreement to MLSS [11, 12]. Joyner & Coyle (2008) updated the existing model by an anaerobic component and stated *“…that truly accurate models of energy turnover during actual competition would require […] calculation of fluxes through multiple metabolic pathways (e. g. total ATP turnover with contributions from both aerobic and anaerobic components […])”*. However, anaerobic parameters have hardly been implemented in predictive performance models of long-distance running, which was recently highlighted in a review article covering a total of 58 studies [13].

A mathematical model designed to describe the regulation of ATP production in muscle cells was introduced by Alois Mader in 2003 [14]. He calculated the fractional utilisation of oxidative phosphorylation and glycolysis as a function of free ADP concentration. Besides $\dot{V}O_2max$, the maximal rate of glycolysis was included in this model, which is formally known as maximal lactate accumulation rate ($\dot{c}La_{max}$). Just recently, the fundamentals of this concept and the corresponding influence of $\dot{c}La_{max}$ on MLSS were extensively summarized [15]. Given the same $\dot{V}O_2max$ *“[…] Mader’s model predicts that athletes with a higher [$\dot{c}La_{max}$] generally have higher lactate concentrations at the same workload [and] reach their [MLSS] at a lower workload […]* [15]. This indicates that higher values of $\dot{c}La_{max}$ result in a lower $\%\dot{V}O_2max$. Hence, augmenting the metabolic profile by means of $\dot{c}La_{max}$ might help understand how metabolic processes interact during exercise, which has direct applications to the individual pacing strategy [16].

In cycling, previous research demonstrated that mathematical simulation approaches allow for calculating maximal lactate steady-state with an acceptable reliability [17, 18] and accuracy [19]. Furthermore, test procedures to determine $\dot{c}La_{max}$ in running have been developed and demonstrated high reliability [20, 21]. Usually, the increase in post-exercise lactate concentration following an 10–15 s all-out sprint test is used to determine $\dot{c}La_{max}$. Hence, the required tools exist to examine if $\dot{c}La_{max}$ is a suitable augmentation of the metabolic profile and whether it is related to $\%\dot{V}O_2max$ in running. This study aims to assess the practical value of $\dot{c}La_{max}$ in terms of improving performance prediction in endurance running.

Materials and Methods

Participants

A total of N = 44 trained endurance athletes (runners n = 24; triathletes n = 20) volunteered to participate in this study. As an inclusion criterion, a 5000-m personal best of 22 and 20 minutes was required for female (n = 15) and male (n = 29) participants, respectively. Participants stated to have an overall weekly training routine and running distance of 11.9 ± 5.4 h and 56.8 ± 24.2 km, respectively and had competitive experienced for 8.0 ± 5.8 years (▶ **Table 1**). Prior to any testing, the participants received a medical check-up based on the guidelines of the European Society of Cardiology (ESC). This check-up includes notation of the individuals' account of their own medical, family and personal history, a physical examination and a resting electrocardiogram [22]. Only participants without positive findings were included. All procedures received institutional ethics approval (No. 008/2019) according to the Declaration of Helsinki. Before the investigation, participants were personally informed about the aims, procedures and potential risks of this study, and gave their written consent.

Design

The design of this study oriented on recent research that examined the physiological determinants of ultramarathon trail-running [23, 24]. Measurements were performed from March to September 2019. The participants had to perform various exercise tests including an incremental step test, a 100-m all-out sprint test, a ramp test and a 5000-m time trial. Tests were performed within one week on Mondays, Wednesdays and Fridays to ensure agreement between physiological and performance related parameters while minimising fatigue between procedures. All participants were instructed to refrain from caffeinated beverages for at least 8 h before testing and to avoid any vigorous physical activity on the testing day and the day before. For gas exchange analyses in the laboratory, participants had to arrive in a carbohydrate-loaded state, but with a fasting period of at least two hours. To avoid influences based on circadian rhythm, the participants performed the laboratory tests on Mondays and Wednesdays at approximately the same time of the day.

On their first visit to the laboratory, the participants were informed about the procedures, received the medical check-up and underwent a ten-site skinfold thickness measurement (Harpenden Skinfold Caliper, Baty Int., West Sussex, United Kingdom) to determine their body fat percentage [25]. Afterwards, the participants performed an incremental step test on a treadmill. On Wednesdays, the participants performed the 100-m all-out sprint test on an indoor track and approximately one hour afterwards a ramp test protocol until subjective exhaustion in the laboratory. On their last visit (Fridays), the participants performed a 5000-m time trial on a 400-m outdoor track. Testing in the laboratory was performed on a motorised treadmill (saturn 300/100, h/p/cosmos sports & medical GmbH, Nussdorf-Traunstein, Germany) with a constant gradient of 1 % [26]. According to the guidelines of the manufacturer, the participants wore a safety belt, which was connected to the automatic security brake system of the treadmill.

Protocols

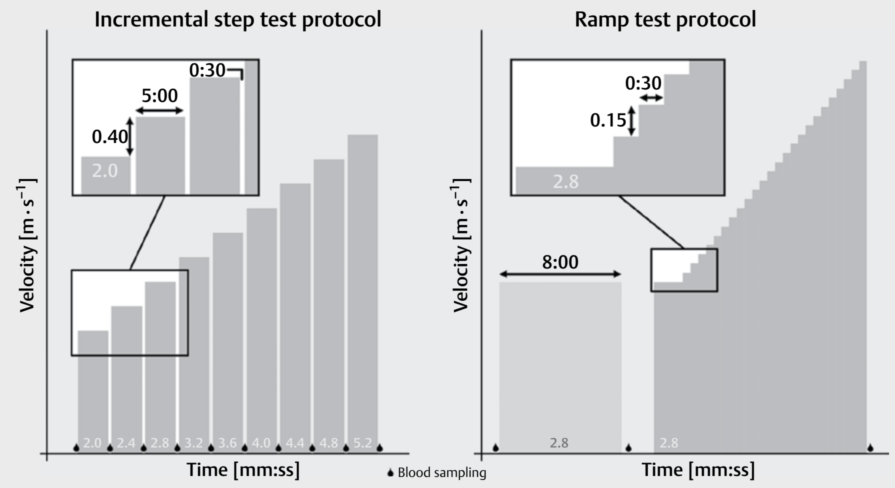
Incremental step test

The incremental step test started with an initial velocity of $2.0\,m \cdot s^{-1}$ ($7.2\,km \cdot h^{-1}$ or $8{:}20\,min \cdot km^{-1}$), which increased by $0.4\,m \cdot s^{-1}$ ($1.44\,km \cdot h^{-1}$) every five minutes as illustrated in ▶ **Fig. 1a**. At the end of every step, the treadmill stopped for 30 seconds in which ratings of perceived exertion [27] were noted and a blood sample (20 µl) was collected from the right earlobe to determine lactate concentration immediately (Biosen C-Line, EKF-diagnostic GmbH, Barleben, Germany). The incremental step test was terminated when blood lactate concentration exceeded $4.0\,mmol \cdot l^{-1}$. Fractional utilization of $\dot{V}O_2max$ ($\%\dot{V}O_2max$) at lactate threshold was interpolated for the velocity according to a fixed lactate concentration of $4\,mmol \cdot l^{-1}$ (v_{OBLA}). Throughout the incremental test, participants wore an airtight silicone oro-nasal mask (7450 Series, V2™, Hans-Rudolph, Inc., Shawnee, KS, United States of America) to record oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) breath-by-breath by a spirometric device (ZAN 600 USB, nSpire Health, Inc., Longmont, CO, United States of America). Flow sensors were calibrated manually by using a standardised 3000 ml high precision syringe (nSpire Health, Inc., Longmont, CO, United States

▶ **Table 1** Descriptive statistics characterising participants and differences between females and males.

Parameter		**Total**	**Females**	**Males**		
		(n = 44)	**(n = 15)**	**(n = 29)**	**d**	**p**
Age	[yrs.]	25.2 ± 4.1	27.1 ± 4.7	24.2 ± 3.4	**0.747***	0.028
Height	[m]	1.77 ± 0.1	1.68 ± 0.06	1.81 ± 0.08	− **1.758*****	< 0.001
Mass	[kg]	66.5 ± 9.2	58 ± 6.4	70.8 ± 7.2	− **1.843*****	< 0.001
Body Fat	[%]	12.5 ± 3.2	13.6 ± 4.9	11.9 ± 1.7	0.539	0.202
Experience	[yrs.]	8.0 ± 5.8	7.5 ± 5.6	8.2 ± 5.9	− 0.121	0.756^{U}
Training	$[h \cdot wk^{-1}]$	11.9 ± 5.4	12.3 ± 4.5	11.6 ± 5.8	0.130	0.683
Training	$[km \cdot wk^{-1}]$	56.8 ± 24.2	62.2 ± 12.0	54.1 ± 28.4	0.332	0.307

Values are expressed as mean value ($\bar{x}$) and standard deviation (SD).; * significant difference between female and male participants ($p \leq 0.05$); *** significant difference between female and male participants ($p \leq 0.001$); ^{U} Comparisons between female and male participants were performed by using the Mann-Whitney-U test.



▶ **Fig. 1** Protocols used for the incremental step test (left) and the ramp test (right).; Occasions for blood sampling to determine lactate concentration are marked by the drop symbol. During the incremental test, gas analyses were provided throughout, whereas the 8 min warm-up preceding the ramp test was performed without gas analyses.

of America). Gas concentration was calibrated under laboratory conditions as well as a gas mixture of 15 % O_2 and 6 % CO_2.

100-m all-out sprint test

The participants performed the 100-m all-out sprint test and the standardised warm-up of 15 minutes including technical drills and starts as described previously [20, 21]. Throughout the sprints, participants were verbally encouraged by the examiners. The time to cover the 100 metres (t_{100}) was determined using a start pedal and a double infrared photoelectric light barrier (Sportronic Electronic Sports Equipment, Winnenden-Herthmannsweiler, Germany). Blood samples were collected immediately before and after the sprint test, as well as every minute after the sprint for 10 minutes.

$\dot{c}La_{max}$ was calculated as the difference between the measured maximal post-exercise lactate concentration and resting lactate concentration (ΔLa_{100}), which was divided by the difference between t_{100} and the period at the beginning of exercise for which no lactate formation is assumed (t_{alac}) (Eq. 1) [20, 21, 28, 29].

$$\dot{c}La_{max} = \frac{\Delta La_{100}}{t_{test} - t_{alac}}$$

As a representation of phosphocreatine metabolism, t_{alac} was interpolated according to previous research (Eq. 2) [20, 28].

$$t_{alac} = t_{100} \,.\, 0.0909 + 2.0455$$

After the last blood sample was collected, participants performed an individual cool-down for 10-min at a self-determined intensity and had to arrive at the laboratory approximately 45 min afterwards.

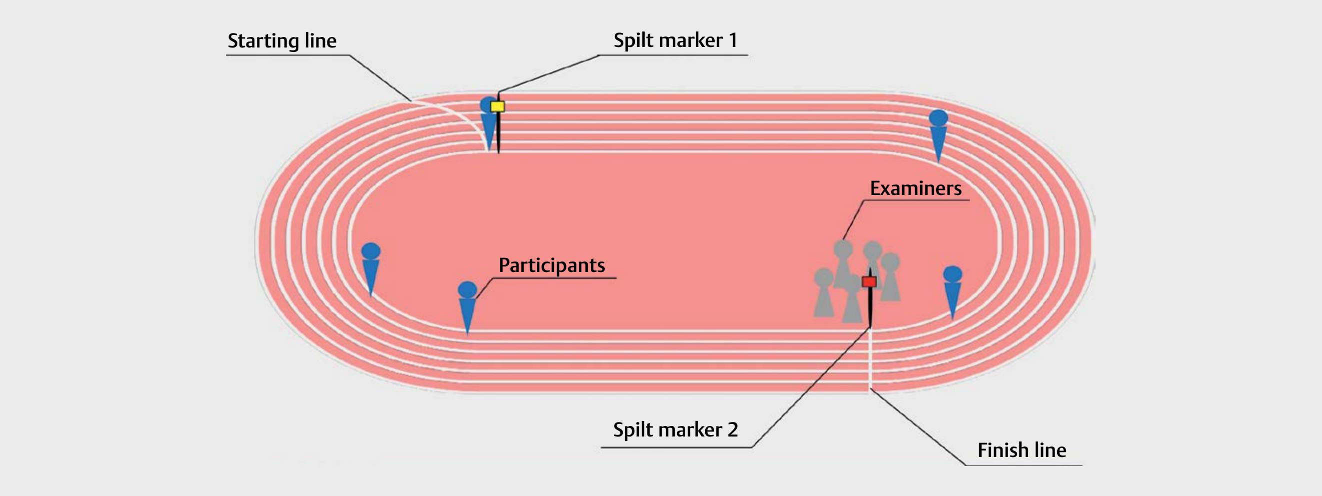
Ramp test

As a warm-up preceding the ramp test protocol, the participants performed eight minutes at 2.8 $m \cdot s^{-1}$ (10.08 $km \cdot h^{-1}$ or 5:57 $min \cdot km^{-1}$) without spirometric measurement (▶ **Fig. 1b**). After a short break for attaching the mask, the ramp test protocol started with an initial velocity of 2.8 $m \cdot s^{-1}$ for another 2 minutes. Afterwards, velocity increased by 0.15 $m \cdot s^{-1}$ (0.54 $km \cdot h^{-1}$) every 30 seconds until subjective exhaustion of the participants. The time to exhaustion (TTE) was noted. Data of gas analysis were averaged for every single 30 second step to determine $\dot{V}O_2max$. The minimal velocity necessary to elicit maximal oxygen uptake ($v\dot{V}O_2max$) was determined as the velocity corresponding to the highest value for oxygen uptake. Anaerobic speed reserve (ASR) was calculated as the difference between the average speed during the 100-m all-out sprint (v_{100}) and $v\dot{V}O_2max$. Blood lactate concentration was determined before and after performing the warm-up as well as immediately after the ramp test protocol. As criteria for $\dot{V}O_2max$, a plateau of ≤ 150 $ml \cdot min^{-1}$, a heart rate of ≥ 95 % HR_{max} (highest values attained in the ramp test or 5000-m time trial), a respiratory exchange ratio (RER) of ≥ 1.05 and a post-exercise lactate concentration of ≥ 8 $mmol \cdot l^{-1}$ were used for evaluation [30]. After the ramp test, participants were encouraged to perform an individual cool-down at a self-determined intensity and duration.

5000-m time trial

The participants started with an easy jog for 10 min at a self-determined intensity on the 400-m track. Afterwards, the participants performed various technical drills for approximately 7 to 10 minutes, followed by four ascending runs of approximately 50 metres. After performing the warm-up, participants had a passive recovery of 5 to 10 minutes before performing the 5000-m time trial. The 5000-m time trial started simultaneously for all participants that had been tested in the respective week (2 to 6 participants). The examiner gave the following instruction regarding the participants' choice of pacing strategy:

"Try to finish the 5000-m in the shortest time possible. This should be the main goal for your attempt. At the end of the race, you should arrive with nothing left in the tank. You can freely choose and adjust your individual pacing strategy. Don't let yourself be distracted by the



▶ **Fig. 2** Schematic illustration of the realisation of 5000-m time trials.; 2–6 individuals (depending of the respective week) started simultaneously at the starting line and performed their individual race to accomplish the 12 ½ rounds in the shortest time possible. The examiners (one examiner per participant) stood near the finish line and measured every single 200-m split resulting in a total of 25 split times. To improve the accuracy of split times, two split markers (javelins) were placed in front of the corners.

pace of the other runners. But try to increase your velocity predominantly towards the end of the race."

Throughout the time trial, the participants wore a sport watch (Garmin Forerunner 920XT, Garmin International, Inc., Olathe, KS, United States of America), which recorded the participants' time, heart rate, cadence and pace. Participants were allowed to take a look at these measures ad libitum. Split times were hand-stopped by one examiner for each runner, who were standing inside the 400-m track near the finish line. To accurately record the participants' 200-m splits, two markers (javelins with flashy pennants at the top) were placed near the beginning of the curves as illustrated in ▶ **Fig. 2**. Participants received verbal feedback every second 200-m split time by their examiner. Additionally, feedback about the remaining laps was given for the last four laps. As a measure of the 'finishing kick', the average velocity during the final 200 m was divided by the average velocity of the preceding 4800 m ($v_{200}/v_{4.8k}$). Lactate concentration was determined before and after the warm-up, as well as immediately before and after performing the 5000-m time trial.

Statistical analyses

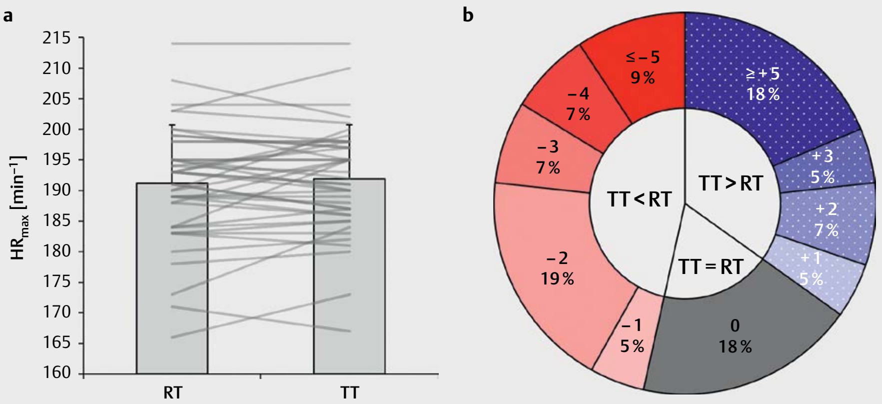
Statistical analyses were done using SPSS (25, IBM SPSS, Armonk, NY, USA). To access which physiological variables significantly predict 5000-m time trial performance (t_{5k}), a stepwise multiple regression analysis was performed. This analysis is in line with previous research focussing on ultramarathon trail-running [23, 24]. However, this study excluded anthropometrics and performance parameters and focussed on purely physiological variables. Physiological variables were entered into the model if there was a significant change in the F-value ($p \leq 0.05$) and by order of their change in R^2. The assumptions of normality, linearity and homoscedasticity were checked visually by using the plot of expected cumulated probability against observed cumulative probability (P-P plot) and the plot of standardized residuals (ZRESID) against standardised predicted values (ZPRED). Independence of errors was assessed by Durbin-Watson statistics (ranging between 0 and 4) with a value of close to two indicating that the residuals are uncorrelated. Collinearity statistics were calculated as tolerance and variance inflation factor (VIF).

Differences between female and male runners were analysed by using independent t-tests in case of normally distributed values in both groups or by using the non-parametric Mann-Whitney U-test. Normality was checked by using the Shapiro-Wilk test ($\alpha > 0.10$), since it is more appropriate for small sample sizes ($N \leq 50$) and more powerful when compared to the Kolmogorov-Smirnov test (even with Lilliefors correction) [31–33]. Analogously, a dependent t-test or Wilcoxon's test were applied for analysing differences between maximal heart rate attained in the ramp test ($HR_{max,RT}$) and during the 5000-m time trial ($HR_{max,5k}$). The individual differences between maximal heart rates were examined visually. As a measure of effect-size, Cohen's d was calculated. Correlation analyses were performed for $\dot{c}La_{max}$ with $\%\dot{V}O_2max$, v_{200}/v_{4800} and ASR by using Pearson's correlation coefficient or alternatively by Spearman's rank correlation in case of significant violations to normal distribution.

Results

A total of $n = 43$ participants performed all exercise tests of this study. One participant attained a calf-muscle strain, which is why data for the 5000-m time trial are missing for this participant. Due to the personal schedule of the participants, the 5000-m time trial was, in few cases ($n = 3$), delayed for one week. Since testings were performed from March to September, ambient temperature during the 5000-m time trials ranged between 10° and 26 °C with drizzling rain on two occasions.

The $\dot{V}O_2max$ criteria of $\leq 150\ ml \cdot min^{-1}$ plateau and a heart rate of $\geq 95\ \%\ HR_{max}$ were met for almost all (except two) participants (96 %). The criteria for $RER \geq 1.05$ and lactate concentration $\geq 8\ mmol \cdot l^{-1}$ were met by 64 and 39 % of the participants, respectively. In total, the participants met at least four (30 %), three



▶ **Fig. 3** Maximal heart rate attained during the ramp test (RT) and 5000-m time trial (TT).; Mean (columns with standard deviation) and individual (lines) comparison between maximal heart rate attained during TT and RT ($d = 0.015$, $p = 0.616$).; Distribution of the difference between maximal heart rate (TT-RT). The unit of the absolute differences is min^{-1}. The grey area indicates that maximal heart rate was equal in TT and RT. The blue areas indicate that maximal heart rate was higher during TT compared to RT. Red areas indicate that maximal heart rate was higher during RT compared to TT.

(68 %), two (96 %) or one (100 %) of these $\dot{V}O_2max$ criteria. All participants stated to be exhausted at the end of the test.

Maximal heart rate did not significantly differ between values attained during the ramp test and the 5000-m time trial ($d = 0.015$, $p = 0.616$). However, a large variation in individual heart rate differences was observed (▶ **Fig. 3a**). Whereas 18 % of the participants attained exactly the same value for maximal heart rate during the ramp test and time trial, 47 % attained a higher value during the ramp test (▶ **Fig. 3b**). However, only half of these individuals demonstrated a difference that exceeded 3 min^{-1}. On the other hand, 35 % of the participants attained a higher maximal heart rate during the time trial with 18 % of all participants demonstrating a difference of at least 5 min^{-1}.

The participants performed the 5000-m time trial at a high percentage of their maximal heart rate, which exceeded 90 % for most of the time (▶ **Fig. 4**). Individual and mean pacing characteristics during the time trial demonstrate a fast start and a high variability at the end. Some participants performed the finish with a very high increase in velocity, while others demonstrated a steadier pace. Cadence demonstrated a high variability between participants and was highest during the start and finish of the race.

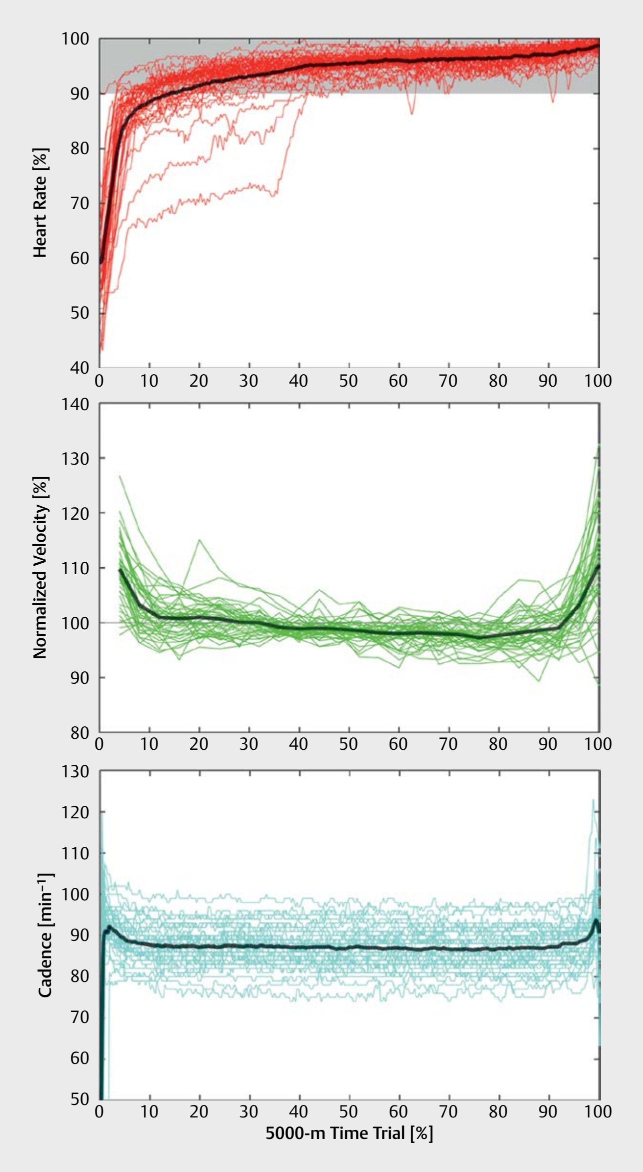
Stepwise multiple regression demonstrated that augmenting Joyner's model ($\dot{V}O_2max$, RE_{OBLA} and $\%\dot{V}O_2max$) by means of $\dot{c}La_{max}$ explained an additional amount of variance ($\Delta R^2 = 4.4\,\%$, $p = 0.006$) in t_{5k} resulting in a total R^2 of 79.8 % (see Supplementary Table). Durbin-Watson statistics resulted in a value of 2.058. Visually examination of the respective plots demonstrated that the criteria for normality, linearity and homoscedasticity were met by the final model (see Supplementary Figure). Tolerance and VIF of the included parameters ranged from 0.627 to 0.777 and 1.332 to 1.595, respectively (▶ **Table 2**). $\dot{V}O_2max$ demonstrated the highest standardized coefficient ($\beta = -0.978$) while $\dot{c}La_{max}$ showed the lowest value ($\beta = -0.244$). However, performing the same analysis exclusively for males, $\dot{c}La_{max}$ was not included in stepwise linear regression.

Female participants demonstrated a lower body mass, lower height and higher age (▶ **Table 1**). Body fat percentage, as well as training experience and volume did not differ between females and males. Regarding performance variables, females had a slower t_{100} and t_{5k} (▶ **Table 3**). Females demonstrated a lower TTE, $v\dot{V}O_2max$, $\dot{V}O_2max$, $\dot{c}La_{max}$, ASR and $v_{200}/v_{4.8k}$. During the ramp test protocol, females demonstrated a lower maximal RER and a lower post-exercise lactate concentration. The lactate concentrations following the sprint test and the 5000-m time trial were also lower in females. No significant differences between females and males could be found in heart rate parameters. $\dot{c}La_{max}$ significantly correlated with ASR ($r = 0.644$, $p < 0.001$), $\%\dot{V}O_2max$ ($r = -0.439$, $p = 0.003$) and $v_{200}/v_{4.8k}$ ($r = 0.389$, $p = 0.010$) (▶ **Fig. 5**).

Discussion

The aim of this study was to assess the practical value of $\dot{c}La_{max}$ in terms of improving performance prediction in a 5000-m time trial. It was found that including $\dot{c}La_{max}$ in a model to calculate 5000-m time trial performance allows to explain a significant amount of variance (+4.4 %) in a mixed-sex group of trained athletes. Females had a slower t_{5k} and a lower $\dot{V}O_2max$, $\dot{c}La_{max}$, ASR and $v_{200}/v_{4.8k}$ compared to males. Furthermore, $\dot{c}La_{max}$ demonstrated a significantly negative correlation with $\%\dot{V}O_2max$ and a positive correlation with $v_{200/4.8k}$ and ASR. Additionally, maximal heart rate showed high inter-individual differences between the ramp test and the 5000-m time trial.

The most important physiological variables to explain 5000-m time trial performance were, in descending order, $\dot{V}O_2max$, RE_{OBLA}, $\%\dot{V}O_2max$ and $\dot{c}La_{max}$. This model sufficiently met the assumptions of normality, linearity, homoscedasticity, non-collinearity and independence of errors indicating adequate dependability of the results. It is important to note that this information has poorly been reported in previous models [13]. In fact, more than 66 % of the variance in 5000-m time trial performance could be explained by



▶ **Fig. 4** Heart rate, velocity and cadence during the course of the 5000-m time trials.; Thick black lines represent the mean values over all participants. Thin coloured lines represent individual values of all participants. Heart rate is expressed as a percentage of maximal heart rate (HR_{max}). Velocity is expressed as a percentage of mean 5000-m velocity (representing 100 %). Cadence was determined by the watch the participants were wearing (Garmin Forerunner 920XT).

$\dot{V}O_2max$ and RE_{OBLA}. An explanation of nearly 80 % of the variance in t_{5k} seems to be rather small when compared to other predictive performance models described in the literature [13, 23, 24]. However, most of these models include parameters that can be characterised as being both, physiological and performance parameter. For example, $v\dot{V}O_2max$ (or maximum velocity in a ramp test) is one of the major variables associated with 5000-m [13] and 50-km performance [23]. The same applies to this very study: $v\dot{V}O_2max$ would have predicted 5000-m time trial performance to a high extend. Including this parameter in our model would have resulted in two problems. Firstly, $v\dot{V}O_2max$ demonstrates a high correlation to $\dot{V}O_2max$ and as such would have increased collinearity. Secondly, this parameter is highly related to the ability to sustain an increasing task until exhaustion [34]. As such, this can be characterised as a kind of performance test that requires anaerobic capabilities as well. In order to assess relevant predictors for 5000-m performance, we decided to implement a purely physiological model. Pastor et al. (2022) demonstrated that 100-km performance was associated with muscular strength and body composition and that longer distances seem to lack prediction by classical physiological variables [24]. As highlighted in their conclusions, the implementation of other variables raleted to (neuro-)muscular fatigue might have improved performance prediction. This is in line with the upcoming concept of 'durability' which was recently highlighted [35].

The significant correlation between $\dot{c}La_{max}$ and $\%\dot{V}O_2max$ indicates a qualitative agreement with the assumptions of Alois Mader [14]. Participants with a higher $\dot{c}La_{max}$ demonstrate a lower $\%\dot{V}O_2max$ (given a similar $\dot{V}O_2max$) [15]. However, given a variance explanation of 20 % and the rather high variability, this finding should not be overrated. It is important to note that this is a first approximation to the way more complex interdependencies described in Mader's model [14, 15, 28]. As in other scientific contexts, the correlation between $\dot{c}La_{max}$ and $\%\dot{V}O_2max$ does not imply causation. Longitudinal studies should augment $\dot{c}La_{max}$ in exercise testing and examine, whether a change in $\dot{c}La_{max}$ is related to a change in $\%\dot{V}O_2max$. This could verify the assumption made in this cross-sectional investigation. Another assumption of this model, that $\%\dot{V}O_2max$ increases with higher values of $\dot{V}O_2max$ [15], could not be verified with the data of this study. In fact, the correlation of these parameters even tended to be negative. Hence, it should be examined what kind of model – other than a pure linear one as applied here – might be the most adequate to describe the relationship between these measures.

Moreover, blood lactate concentration depends on the rate of release and removal, as well as the distribution volume [36]. Medbø & Toska (2001) examined post-exercise lactate concentration following (1-) 2 min of (non-) exhaustive bicycling. They found that the estimated distribution volume changes increases over time and is significantly larger following non-exhaustive exercise when compared to exhaustive cycling from 3 min after exercise onwards [36]. Hence, actual values of $\dot{c}La_{max}$ might be underestimated by using net post-exercise lactate concentration and assuming a constant distribution volume. However, since this study applied a completely different type of exercise (~14-s all-out), we can only speculate about the transferability of these findings. Recent research demonstrated that the interpretation of velocity constants describing lactate exchange and removal should consider the applied modelling approach as well as exercise intensity and duration [37].

Differences between female and male in sprint and endurance performance as well as $\dot{V}O_2max$ agreed with the literature [38]. $\%\dot{V}O_2max$ and RE were similar between sexes, which might be due to the trained performance level of the participants [39]. The difference in $\dot{c}La_{max}$ between sexes is influenced by the mathematical dependence on t_{100}, which was considerably higher in females. Despite the significantly longer exercise time, the pure increase in post-exercise lactate concentration following the sprint was found to be lower in females. This indicates that the net glyco-

▶ **Table 2** Physiological predictors of multiple regression associated with 5000-m time trial performance.

Predictors	b	SE	β	T	p	Tolerance	VIF
Intercept (constant)	36	2.895		**12.544**	< 0.001		
$\dot{V}O_2max$	− 0.264	0.025	− 0.978	**− 10.619**	< 0.001	0.627	1.595
RE_{OBLA}	0.042	0.008	0.423	**5.112**	< 0.001	0.777	1.287
$\%\dot{V}O_2max$	− 0.101	0.023	− 0.364	**− 4.320**	< 0.001	0.751	1.332
$\dot{c}La_{max}$	− 2.246	0.778	− 0.244	**− 2.888**	0.006	0.743	1.347

b = unstandardized coefficients; $\dot{c}La_{max}$ = maximal lactate accumulation rate; p = probability of finding the observed (or more extreme) results when the null hypothesis is assumed to be true; RE_{OBLA} = interpolated running economy corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA); SE = standard error of unstandardized coefficients; T = empirical value of t-statistics; VIF = variance inflation factor; β = standardized coefficients, $\dot{V}O_2max$ = maximal oxygen uptake; $\%\dot{V}O_2max$ = fractional utilization of $\dot{V}O_2max$ at lactate threshold according to a fixed lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA).

lytic power is lower in females, which might result from differences in muscle mass and fibre size contribution.

The positive correlation between $\dot{c}La_{max}$ and $v_{200}/v_{4.8k}$ indicates that the athletes with a higher glycolytic power are capable of performing an even more reinforced ‘finishing kick’. This seems reasonable since spurts of higher intensity put substantial demands on glycolysis in terms of substrate-level phosphorylation. This could have direct applications to athletic practice and the individual racing strategy. However, $\dot{c}La_{max}$ only explained 15 % of the variance found in $v_{200}/v_{4.8k}$ making it hard to provide concrete recommendations. Aside from physiological factors, the anticipatory feedback model also considers psychological and environmental factors to explain modifications in work rate during time trials [16]. In this context, the rate of lactate production and concomitant physiological changes in muscular pH might be potent afferent feedback to optimise individual pacing.

Maximal heart rate assessment appears to be influenced by various factors resulting in rather high inter-individual differences. In contrast to the findings of this study demonstrating similar average values for maximal heart rate during the time trial and ramp test (192 ± 9 vs. 191 ± 9 min^{-1}, respectively), previous research indicated that maximal heart rate is substantially higher during training and competition (> 10 min^{-1}) when compared to a graded exercise test [40]. The discrepancy between studies might result from differences in exercise protocols. A reason for the higher maximal heart rate attained during the time trial when compared with the ramp test could be phenomenon called cardiovascular drift [41]. Cardiovascular drift is characterised as decrease in stroke volume and concomitant increase in heart rate during prolonged aerobic exercise, which might result from an increase in body temperature [42]. Accordingly, previous research demonstrated that heart rate during ramp tests designed to quickly elicit $\dot{V}O_2max$ might not result in true maximal heart rate when compared to other lab tests, field tests or even competitions of longer duration [43, 44]. The same holds for the huge inter-individual variation in maximal heart rate differences between procedures as observed in this study [44]. Given that heart rate increases with ambient temperature, the conditions during the individual time trials might influence the differences seen in maximal heart rate [45]. Another reason for a higher peak heart rate during the time trial could be the difference in the preceding warm-up [43]. In the study of Ingjer (1991), nine out of ten participants demonstrated a higher peak heart rate after performing a 30 min warm-up at 60 % $\dot{V}O_2max$ when compared to a 10 min warm-up at the same intensity. This could again be influenced by the phenomenon of cardiovascular drift [41]. However, given the fact that the warm-ups differed in other factors as well (e. g. technical drills and ascending runs compared to steady running at low-intensity), a direct comparison seems to be challenging. A higher maximal heart rate attained during the ramp tests could result from a fatigue effect occurring for exhaustive exercise when performed on consecutive days [43]. However, given that there was one day of rest between ramp test and the time trial, this influence might be less in this study. Additionally, receiving verbal encouragement throughout the ramp test (as opposed to the time trial in which encouragement was present every 200 to 400 metres) might increase the participants’ motivation to perform well and thus result in higher values of maximal heart rate [46]. However, the same effect was found for head-to-head competitions that were simulated during the time trials. We assume that this effect is moderated by the similarity of the participants’ performance and pacing in the respective time trial resulting in a literally more or less head-to-head competition.

Limitations

A very important aspect worth considering in this study is the fact that multiple regression was applied in a mixed-sex group of endurance athletes. Since females had a significantly lower t_{5k} and $\dot{c}La_{max}$, the significant inclusion of $\dot{c}La_{max}$ might (at least in parts) be influenced by the effect of sex. However, subgroup analyses would have lacked statistical power for multiple regressions covering four predictors for the given effect size. Future studies are encouraged to replicate this study in a larger sample of females or males.

Differing conditions during time trials (e. g. temperature, wind and weather) might influence the agreement between laboratory findings and endurance performance and pacing in the field and the comparison between individual participants. However, previous research comparing a wide range of temperatures (-14 to + 20 °C) at a wind speed of 5 m · s^{-1} did not find an effect on TTE, RE and $\dot{V}O_2max$ in female endurance runners [45]. Hence, we believe that the potential perturbations in time trial resulting from differences in outdoor conditions are in the range of day-by-day variability and do not substantially influence the findings of this study.

▸ **Table 3** Physiological and performance parameters of female and male participants.

Parameter		**Total**	**Female**	**Male**		
		(n = 44)	**(n = 15)**	**(n = 29)**	**d**	**p**
$\dot{V}O_2max$	$[ml \cdot min^{-1} \cdot kg^{-1}]$	60.5 ± 5.7	55.4 ± 3.9	63.2 ± 4.5	$-\mathbf{1.810}^{***}$	$<0.001^{U}$
$v\dot{V}O_2max$	$[m \cdot s^{-1}]$	5.17 ± 0.4	4.8 ± 0.26	5.36 ± 0.31	$-\mathbf{1.903}^{***}$	$<0.001^{U}$
v_{OBLA}	$[m \cdot s^{-1}]$	4.08 ± 0.36	3.88 ± 0.16	4.18 ± 0.4	$-\mathbf{0.884}^{**}$	0.003^{U}
$\%\dot{V}O_2max$	[%]	85.9 ± 5.4	87.6 ± 6	85 ± 4.9	0.491	0.243^{U}
RE_{OBLA}	$[ml \cdot kg^{-1} \cdot km^{-1}]$	213 ± 15	208 ± 11	215 ± 17	−0.459	0.162
RE_{12}	$[ml \cdot kg^{-1} \cdot km^{-1}]$	214 ± 18	209 ± 14	217 ± 19	−0.457	0.220
t_{100}	[s]	13.9 ± 1.35	15.39 ± 1.14	13.14 ± 0.58	$\mathbf{2.775}^{***}$	$<0.001^{U}$
ASR	$[m \cdot s^{-1}]$	2.08 ± 0.50	1.73 ± 0.43	2.27 ± 0.44	$-\mathbf{1.237}^{***}$	< 0.001
$\dot{c}La_{max}$	$[mmol \cdot l^{-1} \cdot s^{-1}]$	0.67 ± 0.16	0.55 ± 0.13	0.74 ± 0.14	$-\mathbf{1.389}^{***}$	< 0.001
t_{5k}	[min]	19.05 ± 1.51	20.43 ± 1.02	18.31 ± 1.18	$\mathbf{1.880}^{***}$	< 0.001
$v_{200}/v_{4.8k}$	[%]	110.9 ± 9.7	105.9 ± 8.4	113.6 ± 9.4	$-\mathbf{0.849}^{*}$	0.011
RER_{max}		1.12 ± 0.2	1.05 ± 0.05	1.16 ± 0.23	$-\mathbf{0.579}^{**}$	0.006^{U}
TTE	[min]	8.43 ± 1.35	7.1 ± 0.85	9.12 ± 1	$-\mathbf{2.120}^{***}$	$<0.001^{U}$
$HR_{max,ST}$	$[min^{-1}]$	187 ± 10	186 ± 13	187 ± 9	−0.095	0.766
$HR_{max,RT}$	$[min^{-1}]$	191 ± 9	188 ± 12	193 ± 7	−0.557	0.114
$HR_{max,5k}$	$[min^{-1}]$	192 ± 9	189 ± 11	193 ± 7	−0.466	0.242
$HR_{mean,5k}$	$[min^{-1}]$	179 ± 10	175 ± 13	181 ± 8	−0.600	0.110
HR_{OBLA}	$[min^{-1}]$	181 ± 10	180 ± 12	181 ± 8	−0.105	0.655
HR_{OBLA}	$[\%HR_{max}]$	93.6 ± 2.8	94.5 ± 2.5	93.1 ± 2.8	0.518	0.090^{U}
$HR_{mean,5k}$	$[\%HR_{max}]$	92.8 ± 2.5	92.1 ± 3.3	93.2 ± 2.5	−0.322	0.476^{U}
$La_{max,ST}$	$[mmol \cdot l^{-1}]$	6.04 ± 1.29	6.18 ± 1.21	5.97 ± 1.35	0.161	0.512^{U}
$La_{post,RT}$	$[mmol \cdot l^{-1}]$	7.15 ± 1.76	6.42 ± 1.99	7.52 ± 1.53	$-\mathbf{0.648}^{*}$	0.026
$La_{post,5k}$	$[mmol \cdot l^{-1}]$	8.48 ± 2.34	7.51 ± 1.92	9.01 ± 2.4	$-\mathbf{0.667}^{*}$	0.044
ΔLa_{100}	$[mmol \cdot l^{-1}]$	6.99 ± 1.23	6.43 ± 1.25	7.27 ± 1.14	$-\mathbf{0.713}^{*}$	0.029
ΔLa_{RT}	$[mmol \cdot l^{-1}]$	5.87 ± 1.74	5.31 ± 2.06	6.16 ± 1.5	$-\mathbf{0.498}^{*}$	0.045
ΔLa_{5k}	$[mmol \cdot l^{-1}]$	6.49 ± 2.18	5.87 ± 1.97	6.82 ± 2.24	−0.442	0.177

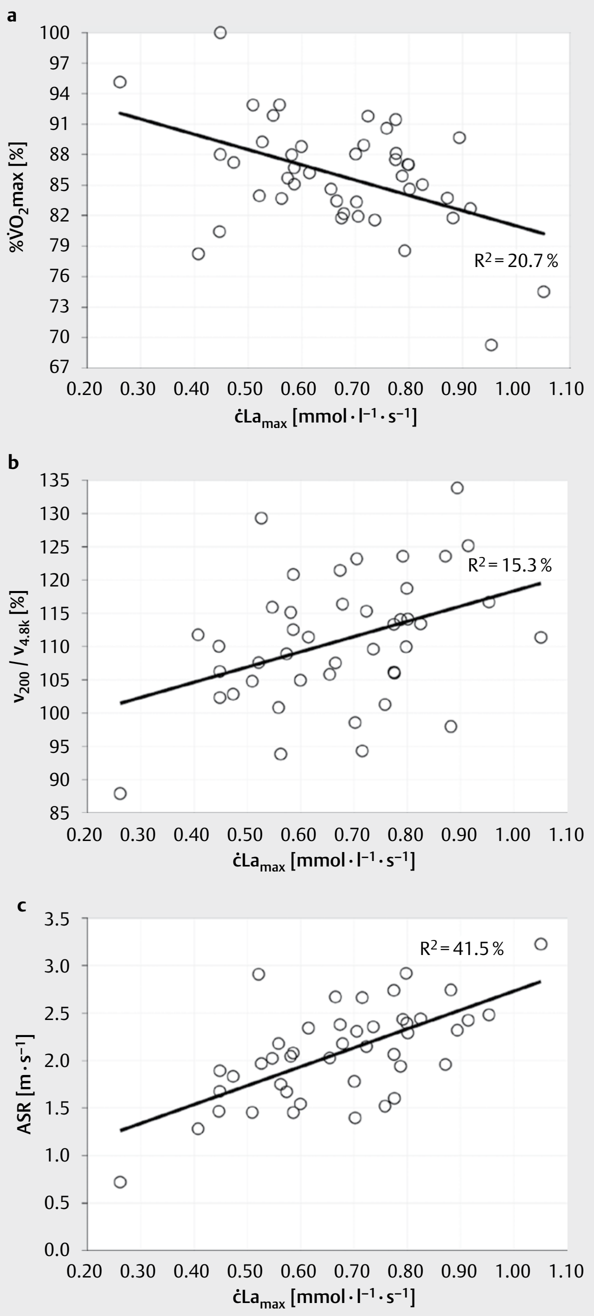
Values are expressed as mean value ($\bar{x}$) and standard deviation (SD).; * significant difference between female and male participants ($p \leq 0.05$); ** significant difference between female and male participants ($p \leq 0.01$); *** significant difference between female and male participants ($p \leq 0.001$); ^{U} Comparisons between female and male participants were performed by using the Mann-Whitney-U test.; ASR = anaerobic speed reserve which was calculated as the difference between the average speed during the 100-m all-out sprint and the minimal velocity necessary to elicit maximal oxygen uptake; $\dot{c}La_{max}$ = maximal lactate accumulation rate; d = Cohen's d effect-size; $HR_{max,5k}$ = maximal heart rate attained during the 5000-m time trial; $HR_{max,RT}$ = maximal heart rate attained during the ramp test protocol; $HR_{max,ST}$ = maximal heart rate attained during the incremental step test protocol; $HR_{mean,5k}$ = mean heart rate attained during the 5000-m time trial; HR_{OBLA} = interpolated heart rate corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA); $La_{max,ST}$ = maximal lactate concentration attained during the incremental step test protocol; $La_{post,5k=}$ lactate concentration immediately after performing the 5000-m time trial; $La_{post,RT}$ = lactate concentration immediately after performing the ramp test protocol; p = probability of finding the observed (or more extreme) results when the null hypothesis is assumed to be true; RE_{12} = interpolated running economy at 12 km · h^{-1}; RE_{OBLA} = interpolated running economy corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA); $RER_{max=}$ maximal respiratory exchange ratio attained during the ramp test protocol; t_{100} = time to perform the 100-m all-out sprint; t_{5k} = time to perform the 5000-m time trial; TTE = time to reach subjective exhaustion during the ramp test protocol (excluding the time to perform the warm-up); $v_{200}/v_{4.8k}$ = ratio of the mean velocity during the final 200-m of the 5000-m time trial ('finishing kick') and the mean velocity attained during the prior 4800-m; v_{OBLA} = interpolated velocity corresponding to a lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA); $\dot{V}O_2max$ = maximal oxygen uptake; $\dot{V}O_2max$ = minimal velocity necessary to elicit maximal oxygen uptake; $\%\dot{V}O_2max$ = fractional utilization of $\dot{V}O_2max$ at lactate threshold according to a fixed lactate concentration of 4 mmol · l^{-1} (onset of blood lactate accumulation, OBLA); ΔLa_{100} = maximal post-exercise increase in lactate concentration following the 100-m all-out sprint test ; ΔLa_{RT} = increase in lactate concentration during the course of the ramp test protocol; $\Delta La_{5k=}$ increase in lactate concentration during the course of the 5000-m time trial.

Even though $\%\dot{V}O_2max$ based v_{OBLA} as a frequently used lactate threshold of 4 mmol · l^{-1}[11], there is reason to debate why we did not use other (ventilatory) thresholds instead. Some researchers argue that lactate and ventilatory thresholds can be seen as surrogates in cycling [47] and running [48], since both concept result in similar intensities and demonstrate a similar degree of reliability [49, 50]. However, other studies highlight the caveats of ventilatory thresholds in terms of objectivity and reliability [51, 52]. Since both approaches seem to be equally effective for estimating the beginning of the high-intensity domain in terms of MLSS [53], and the fact that v_{OBLA} was equally reliable when compared to 'individual' lactate thresholds in cycling [54], we feel that the applied lactate threshold is an adequate measure. However, especially in the context of mathematical simulation approaches – as already conducted in cycling – one should be aware of the potential differences between %$\dot{V}O_2$max at MLSS and v_{OBLA} in the outcomes. To overcome this bias, future research aiming to validate simulation approaches in running should determine %$\dot{V}O_2$max as the $\dot{V}O_2$ measured in a continuous trial at MLSS velocity.

Despite stepwise linear regression analyses are frequently used, they have been criticised for including nuisance variables that reduce the out-of-sample accuracy [55]. It was stated that the probability of including nuisance variables increases with the number of potential predictors (candidates) [55]. The number of candidates used in our study was even lower than the lowest count applied in Monte Carlo simulation. Hence, we argue that the low number of candidates applied in this study reduces the risk for including nuisance variables. However, recently published studies examining the determinants of Ultramarathon Trail-running performance applied stepwise multiple regression analyses without discussing methodical caveats [23, 24].

Maximum rate of glycolysis in terms of $\dot{c}La_{max}$ was derived from post-exercise lactate concentrations following a 100-m sprint. [20, 21]. One might argue that the applied exercise duration (10–15 s) is too short for inducing high reading of lactate concentration and that a 30-s Wingate is more suitable for achieving this [56–58]. However, given that glycolysis increasingly inhibits its key enzyme phosphofructokinase (due to a concomitant reduction intracellular pH) [59], applying exercises beyond 15 s would lead to premature fatigue and, as such, impede to determine the maximal *rate* of glycolysis. This phenomenon has been demonstrated and described in recent investigation [60] and in a narrative review [15]. Since recent research indicates that $\dot{c}La_{max}$ is sport-specific as it does not correlate between cycling and running [21], the application of a short all-out test in running seems to be applicable here.

The significant correlation between $\dot{c}La_{max}$ and ASR are influenced by the mathematical dependence on t_{100}, which is used in the calculation of both parameters. However, even pure ΔLa_{100} explained almost 22 % of the variance ASR. It is important to note that ASR was calculated by using the mean and not maximal velocity attained during the 100-m sprint. Hence, absolute values of ASR are not comparable to other research indicating considerably higher values [61–63]. Based on the correlation between t_{100} and maximal sprint speed, future studies might apply corresponding relationships to re-calculate the values in this study [61].



▶ **Fig. 5** Relationships between maximal lactate accumulation rate ($\dot{c}La_{max}$) and other physiological and performance parameters.; a) Correlation between $\dot{c}La_{max}$ and the fractional utilisation of $\dot{V}O_2$max at lactate threshold (%$\dot{V}O_2$max) according to a fixed lactate concentration of 4 mmol · l⁻¹.; b) Correlation between $\dot{c}La_{max}$ and the finishing kick during the 5000-m time trial. The finishing kick is expressed as the ratio between the average velocity during the last 200-m of the 5000-m time trial and the average velocity during the preceding 4800 metres ($v_{200}/v_{4.8k}$).; c) Correlation between $\dot{c}La_{max}$ and the anaerobic speed reserve (ASR). ASR was calculated as the difference between the average speed during the 100-m all-out sprint (v_{100}) and the minimal velocity necessary to elicit maximal oxygen uptake ($v\dot{V}O_2$max).; All relationships attained statistical significance with a) $p = 0.003$ b) $p = 0.010$ and c) $p \leq 0.001$.

Conclusion

The present findings indicate that $\dot{c}La_{max}$ allows for significant (yet minor) improvements in 5000-m performance prediction in a mixed-sex group and it is related to %$\dot{V}O_2$max and the ‘finishing kick’. This expands the established performance models by means of an anaerobic capability, which is relevant for understanding exercise physiology and performance. Since $\dot{c}La_{max}$ testing is a time-efficient procedure and does not restrict the athletes’ training schedule, scientists and coaches are encouraged to implement it in practice. Future studies need to replicate this analysis in middle-distance events and examine differences in their predictability. Longitudinal studies examining the effects of deliberate training on $\dot{c}La_{max}$ are sparse and thus of particular interest.

Athletes aiming to improve their 'finishing-kick' might need to increase their $\dot{c}La_{max}$ in order to provide the required power of glycolytic metabolism. However, since this study investigated pacing only in terms of the 'finishing kick', future research should identify pacing strategies over the complete time trial distance. Such pacing clusters could be compared by means of their performance outcomes and physiological characteristics to improve the understanding of individual pacing in running. Athletes aiming to elicit HR_{max} should be aware of the high inter-individual differences between procedures, which directly affect training prescription based on $\%HR_{max}$. In search of the most effective testing procedures, research needs to further explore individual heart rate responses to different exercise protocols.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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