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A modified formula using energy system contributions to calculate pure maximal rate of lactate accumulation during a maximal sprint cycling test

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Purpose: This study aimed at comparing previous calculating formulas of maximal lactate accumulation rate ($v_{La,max}$) and a modified formula of pure $v_{La,max}$ ($Pv_{La,max}$) during a 15-s all-out sprint cycling test (ASCT) to analyze their relationships.

Methods: Thirty male national-level track cyclists participated in this study ($n = 30$) and performed a 15-s ASCT. The anaerobic power output (W_{peak} and W_{mean}), oxygen uptake, and blood lactate concentrations (La^-) were measured. These parameters were used for different calculations of $v_{La,max}$ and three energy contributions (phosphagen, W_{PCr} ; glycolytic, W_{Gly} ; and oxidative, W_{Oxi}). The $Pv_{La,max}$ calculation considered delta La^- , time until W_{peak} ($t_{PCr-peak}$), and the time contributed by the oxidative system (t_{Oxi}). Other $v_{La,max}$ levels without t_{Oxi} were calculated using decreasing time by 3.5% from W_{peak} ($t_{PCr-3.5\%}$) and $t_{PCr-peak}$.

Results: The absolute and relative W_{PCr} were higher than W_{Gly} and W_{Oxi} ($p < 0.0001$, respectively), and the absolute and relative W_{Gly} were significantly higher than W_{Oxi} ($p < 0.0001$, respectively); $v_{La,max}$ ($t_{PCr-3.5\%}$) was significantly higher than $Pv_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$), while $v_{La,max}$ ($t_{PCr-peak}$) was lower than $Pv_{La,max}$ ($p < 0.0001$, respectively). $Pv_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$) were highly correlated ($r = 0.99$; $R^2 = 0.98$). This correlation was higher than the relationship between $Pv_{La,max}$ and $v_{La,max}$ ($t_{PCr-3.5\%}$) ($r = 0.87$; $R^2 = 0.77$). $v_{La,max}$ ($t_{PCr-peak}$), $Pv_{La,max}$, and $v_{La,max}$ ($t_{PCr-3.5\%}$) were found to correlate with absolute W_{mean} and W_{Gly} .

Conclusion: $Pv_{La,max}$ as a modified calculation of $v_{La,max}$ provides more detailed insights into the inter-individual differences in energy and glycolytic metabolism than $v_{La,max}$ ($t_{PCr-peak}$) and $v_{La,max}$ ($t_{PCr-3.5\%}$). Because W_{Oxi} and W_{PCr} can differ remarkably between athletes, implementing their values in $Pv_{La,max}$ can establish more optimized individual profiling for elite track cyclists.

KEYWORDS

anaerobic performance, diagnostics, glycolytic metabolism, lactate, anaerobic power output

Introduction

Three human energy systems (phosphagen, glycolytic, and oxidative systems) are simultaneously used during different exercises (Beneke et al., 2002; Yang et al., 2020; Yang et al., 2022a; Yang et al., 2022b). However, their relative energy contribution, particularly the energy systems that are predominantly utilized at a given moment, depends critically on the exercise intensity and duration (Beneke et al., 2002; Yang et al., 2022b). Therefore, precise determinations of energetic contributions during specific sports are crucial for a better understanding of physiological responses to enhance exercise prescriptions (Julio et al., 2017; Franchini, 2020; Yang et al., 2022b).

Among various Olympic disciplines, there are sections such as football, handball, basketball, rugby, and track cycling (Hettinga et al., 2007; Wackerhage et al., 2022), in which maximal anaerobic power and capacity are essential to achieve a highly competitive performance. For instance, the anaerobic capacity of track cyclists is exploited during a 1,500-m Keirin race over approximately 90–120 s (Foster et al., 1993; Hettinga et al., 2007). A crucial factor that determines the winner of such races is particularly the final all-out sprint to the finish line (Fujii et al., 2018). Although a high aerobic performance is absolutely necessary, these athletes also require high anaerobic power (Hettinga et al., 2007; Fujii et al., 2018). The anaerobic performance of athletes (e.g., 100-m sprint) is proportional to their individual anaerobic energy capacity (Yang et al., 2020; Park et al., 2021; Yang et al., 2022b). The phosphagen system (adenosine triphosphate and phosphocreatine, ATP-PCr) ensures the highest metabolic power or energy flux rate, which is reflected by the rate of energy transfer per unit of time. Although the energy flux rate is very high, the general capacity is low because of limited substrate stores that lasts for only a few muscle contractions (Gastin, 2001; Robergs et al., 2004). The glycolytic system can re-synthesize ATP through the non-aerobic degradation of carbohydrates and supports the metabolic energy requirements during intense exercise. This system, when compared to the phosphagen system, is characterized by an intermediate energy flux rate and metabolic power because of the higher number of reactions and greater overall capacity from a large amount of stored carbohydrates (Gastin, 2001; Robergs et al., 2004; Franchini, 2023). In this regard, the Mader's (1984) model proposed considering individual maximal glycolytic rates ($v_{La,max}$) to be utilized while determining the maximal glycolysis and power after an all-out sports-specific sprint test (Hauser et al., 2014; Quittmann et al., 2020; Quittmann et al., 2021; Wackerhage et al., 2022). Accordingly, athletes in sprint sports can maximally produce over 1.0 mmol lactate per liter per second (i.e., $\geq 1.0 \text{ mmol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}$) (Wackerhage et al., 2022).

The formula of $v_{La,max}$ (Mader, 1984) is considered the delta lactate concentration (ΔLa^-) between maximal blood La^- accumulation after exercising and resting blood La^- levels are divided by the difference between the total exercise time (t_{exer}) and phosphagen system-contributed time (t_{PCr}). Here, t_{PCr} is assumed as the period in which no La^- formation ("fictitiously") takes place, beginning from the start of the maximal power output until it is reduced by 3.5% (the point of -3.5% from the peak watt, $t_{\text{PCr}-3.5\%}$). Previous studies have used the $t_{\text{PCr}-3.5\%}$ definition without providing an in-depth explanation on why the reduced

3.5% time point of the maximal power output was determined as t_{PCr} (Hauser et al., 2014; Adam et al., 2015; Nitzsche et al., 2018; Quittmann et al., 2020; Quittmann et al., 2021). However, this assumption likely originates from the precision of power measurement of an early SRM cycle ergometer (Weber, 2003). Another t_{PCr} definition was determined as the time until peak watt ($t_{\text{PCr-peak}}$) during the $v_{La,max}$ test (Manunzio et al., 2016).

Indeed, the determination of $v_{La,max}$ via these calculations may further have imprecisions with the involvement of oxidative energy metabolism, also in short time frames of exercising, when it is not separately subtracted from the total energy demand. Interestingly, previous studies have reported that oxidative energy metabolism is not considered in the $v_{La,max}$ formula, which contributes to a total energy expenditure of approximately 10% during the 100-m sprint (Heck et al., 2003; Quittmann et al., 2020; Park et al., 2021).

Also, calculations of the Mader's model include the oxidative contribution timespan and not subtracting the energy contribution of oxidative metabolism. When considering an approximate contribution of 10% during short sprints, a "pure" $v_{La,max}$ determination during the maximal anaerobic cycling test cannot be precisely calculated. To determine $v_{La,max}$, we minimize the oxidative contribution and lactate elimination during the aftermath of the test; its duration should be limited between 10 and 15 s (Heck et al., 2003; Quittmann et al., 2020). In this context, the PCr- La^- - O_2 method is yet another well-established methodology involving all three energy system contributions when calculating exercise-induced energy turnover (Beneke et al., 2004; de Moraes Bertuzzi et al., 2007; de Campos Mello et al., 2009; Hausen et al., 2017; Julio et al., 2017; Yang et al., 2018; Park et al., 2021; Yang et al., 2022b; Kaufmann et al., 2022). This method can easily be incorporated into the $v_{La,max}$ formula as the time ratio of relative oxidative contribution (%) and then be used to calculate an optimized $v_{La,max}$ (Beneke et al., 2004; de Moraes Bertuzzi et al., 2007; de Campos Mello et al., 2009; Campos et al., 2012; Hausen et al., 2017; Julio et al., 2017; Lopes-Silva et al., 2018; Yang et al., 2018; Franchini, 2020; Park et al., 2021; Yang et al., 2022b).

Therefore, this study compares three different $v_{La,max}$ calculations based on the differences in determining the phosphagen-contributed time and incorporation of the oxidative energy system: first, $v_{La,max}$ by using $t_{\text{PCr}-3.5\%}$; second, $v_{La,max}$ by using $t_{\text{PCr-peak}}$ determinations; and third, by subtracting the contribution of the oxidative energy metabolism during a 15-s maximal sprint cycling test. The latter is substituted with a modified pure $v_{La,max}$ ($Pv_{La,max}$) formula using the analysis of the PCr- La^- - O_2 method. Finally, the relationships among the different $v_{La,max}$ calculations, mean power output, and glycolytic energy contribution are analyzed.

Materials and methods

Participants

With an effect size of 0.32, an alpha error probability of 0.05, and statistical power of 0.95, the sample size was calculated using the G*Power software, version 3.1.9.4 (Heinrich Heine University, Düsseldorf, Germany). The effect size was considered based on previous studies (Hauser et al., 2014; Manunzio et al., 2016; Fujii

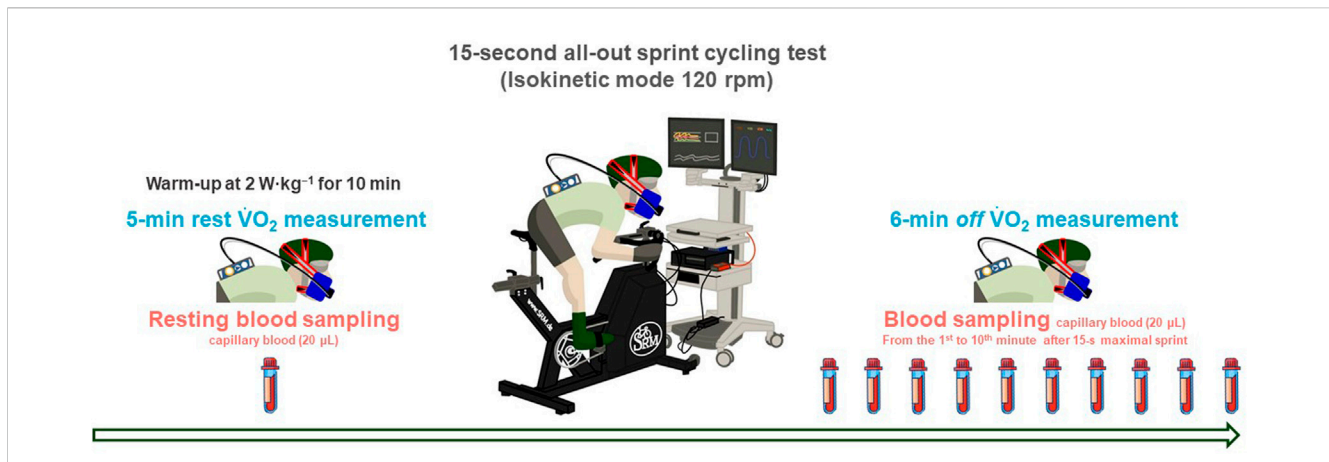


FIGURE 1

Study procedure. An initial warm-up was performed for 10 min at $2 \text{ W}\cdot\text{kg}^{-1}$. A further passive rest for 5 min followed. A 15-s all-out sprint cycling test was performed in the isokinetic mode set to a cadence of 120 rpm. Participants performed the test in the sitting position on the ergometer. Oxygen uptake at 5-min rest, and during as well as up to 6 min after 15-s all-out sprint cycling test was measured. Capillary blood was collected from the earlobe ($20 \mu\text{L}$) before and in minutes' interval (1st to 10th) after the 15-s all-out sprint cycling test. $\dot{V}\text{O}_2$, oxygen uptake.

et al., 2018; Quittmann et al., 2020; Quittmann et al., 2021). Considering a 10% dropout rate, 30 male national-level track cyclists were enrolled in this study. All participants were track cyclists (main discipline: Keirin) who train for 18–20 h per week. They have been enrolled in the Korean national championships over the last 8 years. The anthropometric parameters of these participants are age: 30 ± 6 years; height: 177.30 ± 6.21 cm; body mass: 85.11 ± 9.89 ; and body fat: $19.16\% \pm 4.78\%$. The participants had rested for 2 h after lunchtime and performed a 15-s all-out sprint cycling test (ASCT). They were instructed not to take any coffee, neuro stimulants, or medication immediately before the test. Alcohol and nicotine was not consumed at least 24 h before the experiment. The Institutional Review Board of CHA University approved this study (No. 1044308-202206-HR-032-02). Study protocols followed the ethical standards in the Declaration of Helsinki. All participants had signed an informed consent form.

Study procedure

All participants attended a single laboratory session. The test procedure was conducted and controlled in the same laboratory environment throughout testing (temperature: 23°C and relative humidity: 50%). The anthropometric parameters were measured with an eight-electrode segmental multi-frequency bioelectrical impedance analysis (20–100 kHz; InBody 270; InBody Co., Ltd., Seoul, Republic of Korea). Before the 15-s ASCT, the latest SRM ergometer (No. 2203, 04/2022, Schoberer Rad Messtechnik, GmbH, Jülich, Germany) was set up to fit each participant's track bicycle position (i.e., crank length, saddle height, handle height, and saddle fore-aft position). An initial warm-up was performed for 10 min at $2 \text{ W}\cdot\text{kg}^{-1}$. They further rested passively in the sitting position on the ergometer for 5 min (Figure 1). The 15-s ASCT was performed according to the manufacturer's guidelines in an isokinetic mode set to a cadence of 120 rpm (Manunzio et al., 2016) in the ninth gear and with a 9.1 kg flywheel. The start and end of the 15-s ASCT were

verbally announced by countdown. These settings enabled a reduction in the pedal force in a linear fashion during the initial acceleration phase and achieving a target pedaling rate of 120 rpm after ~ 4 s (Manunzio et al., 2016; Dunst et al., 2023). The participants performed the test in the sitting position on the ergometer. They were verbally encouraged by the investigator to generate the maximum possible power output. Afterward, the absolute and relative peak and mean power outputs in watt and $\text{W}\cdot\text{kg}^{-1}$ were determined (W_{peak} and W_{mean} , respectively) (Hauser et al., 2014; Manunzio et al., 2016; Quittmann et al., 2020; Quittmann et al., 2021). Oxygen uptake (resting oxygen uptake, $\dot{V}\text{O}_{2\text{rest}}$; average oxygen uptake during the 15-s ASCT, $\dot{V}\text{O}_{2\text{mean}}$; highest oxygen uptake during the 15-s ASCT, $\dot{V}\text{O}_{2\text{peak}}$; and fast component of excess oxygen consumption [$\text{EPOC}_{\text{fast}}$], off $\dot{V}\text{O}_2$ kinetics) at 5-min rest, and during and after the 15-s ASCT (6 min) were measured using the breath-by-breath method with a portable gas analyzer (METAMAX 3B, Cortex Biophysik, Leipzig, Germany) that was placed on the back of the participants. The portable gas analyzer was calibrated with the calibration gas (15% O_2 and 5% CO_2 ; Cortex Biophysik, Leipzig, Germany), and the turbine volume transducer was calibrated using a 3-L syringe (Hans Rudolph, Kansas, United States). $\dot{V}\text{O}_{2\text{mean}}$ and $\dot{V}\text{O}_{2\text{peak}}$ were calculated as the average and highest values during the 15-s ASCT, respectively. Capillary blood was collected from the earlobe ($20 \mu\text{L}$) before and, in minute intervals (1st to 10th), after the 15-s ASCT to determine rest and maximal lactate concentrations (La_{rest} and La_{max} ; the maximal value of La^- among the 10 values) using an enzymatic-amperometric sensor chip system (Biosen C-line; EKF diagnostics sales, GmbH, Barleben, Germany).

Calculations of energetic contributions (PCr-La⁻-O₂ method)

Phosphagen (W_{PCr}), glycolytic (W_{Gly}), and oxidative (W_{Oxi}) contributions in kilojoules, and their percentages were calculated by

measuring $\dot{V}O_2$ and La^- (PCr- La^- - O_2) before, during, and after the 15-s ASCT (Julio et al., 2017; Yang et al., 2018; Yang et al., 2022b; Kaufmann et al., 2022).

W_{PCr} was calculated using $\dot{V}O_2$ after the 15-s ASCT and the fast component of excess post-exercise after the 15-s ASCT (Gastin, 2001; Beneke et al., 2004; Yang et al., 2022b). $\dot{V}O_2$ kinetics after the 15-s ASCT was fitted by mono-exponential and bi-exponential models using the OriginPro 2021 software (OriginLab Corp, Northampton, United States). The slow component of the bi-exponential model was negligible. Thus, $\dot{V}O_2$ data after the 15-s ASCT were fitted using a mono-exponential model, and W_{PCr} was obtained by calculating the integral of the exponential area (Beneke et al., 2004; Campos et al., 2012; Julio et al., 2017; Yang et al., 2018; Yang et al., 2022b; Kaufmann et al., 2022).

The W_{Gly} calculation was performed by determining La^- before and after the 15-s ASCT (La_{rest} and La_{max}), assuming that the production of $1 \text{ mmol}\cdot\text{L}^{-1}$ was equivalent to $3 \text{ mL } O_2\cdot\text{kg}^{-1}$ of body mass (di Prampero and Ferretti, 1999). The difference in La^- (ΔLa^-) was determined by La^- after the 15-s ASCT minus La^- before the 15-s ASCT (Beneke et al., 2004; Campos et al., 2012; Yang et al., 2018; Yang et al., 2022b).

The W_{Oxi} contribution was calculated by subtracting $\dot{V}O_{2rest}$ from $\dot{V}O_2$ during the 15-s ASCT by the trapezoidal method in which the area under the curve was divided into sections and the sum of the trapezoid was used to calculate the integral (de Campos Mello et al., 2009; Yang et al., 2022b). The $\dot{V}O_{2rest}$ value was determined in the sitting position on the cycle ergometer in the last 30 s of the 5-min phase used as a reference (di Prampero and Ferretti, 1999; Beneke et al., 2002; Beneke et al., 2004; Julio et al., 2017; Yang et al., 2018; Kaufmann et al., 2022; Yang et al., 2022b). A caloric quotient of 20.92 kJ was used in the three energy system calculations (Gastin, 2001). The total energy expenditure was determined as the sum of the three energy systems in kilojoules (W_{PCr} , W_{Gly} , and W_{Oxi}) (Campos et al., 2012). The relative contribution of each of the three energy systems was calculated in percentage and compared with the total energy expenditure.

Different formulas of $\nu_{La,max}$ calculations

$\nu_{La,max} (t_{PCr -3.5\%})$ was calculated as ΔLa^- between La_{rest} and La_{max} , which was divided by the difference between the total exercise time (t_{Exer}) and the -3.5% time point from the peak watt ($t_{PCr -3.5\%}$) (Mader, 1984; Weber, 2003) (Eq. 1):

$$\nu_{La,max} (t_{PCr -3.5\%}) [\text{mmol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}] = \frac{La_{max} - La_{rest}}{t_{Exer} - t_{PCr -3.5\%}} \quad (1)$$

Furthermore, only t_{PCr} was differently determined according to previous studies (Serresse et al., 1988; Beneke et al., 2002; Manunzio et al., 2016) (Eq. 2):

$$\nu_{La,max} (t_{PCr-peak}) [\text{mmol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}] = \frac{La_{max} - La_{rest}}{t_{Exer} - t_{PCr-peak}} \quad (2)$$

The accuracy of the latest SRM cycle ergometer (power meter in the science system) is reported to be ± 0.5 – 1% according to the manufacturer and previous studies (Bouillod et al., 2017; Nimmerichter et al., 2017; Montalvo-Pérez et al., 2021). Therefore, a representation of $t_{PCr-peak}$ was determined as the time until W_{peak} during the 15-s ASCT because energy

was influenced by the ATP-PCr system until peak power during the initial seconds of a maximal short-term exercise (Serresse et al., 1988; Beneke et al., 2002).

A modified pure $\nu_{La,max}$ was calculated as ΔLa^- divided by the difference between t_{Exer} and $t_{PCr-peak}$ plus relative W_{Oxi} in percentage of the PCr- La^- - O_2 method during the 15-s ASCT. This percentage was converted to time in seconds (t_{Oxi}) related to the total ASCT time (Eq. 3):

$$P^{\nu}_{La,max} [\text{mmol}\cdot\text{L}^{-1}\cdot\text{s}^{-1}] = \frac{La_{max} - La_{rest}}{t_{Exer} - (t_{PCr-peak} + t_{Oxi})} \quad (3)$$

Statistical analyses

All collected data were analyzed using GraphPad Prism 9.4.1. (GraphPad Prism Software Inc., La Jolla, CA, United States). The data of collected parameters are presented as mean \pm standard deviation (SD). The normal distribution of all data was performed using the Shapiro–Wilk test. The contributions of the three energy systems and different $\nu_{La,max}$ values were compared using a repeated-measures analysis of variance (ANOVA) with the Bonferroni *post hoc* test. The Mauchly’s sphericity test was used to determine whether the assumption of sphericity was being violated by the data. The Greenhouse–Geisser correction was required when necessary. A comparison between $t_{PCr -3.5\%}$ and $t_{PCr-peak}$ was conducted using a paired *t*-test. The significance level was set at $p < 0.05$. The effect sizes (partial eta squared [η_p^2] and Cohen’s [d]) were calculated for the main effect. The thresholds for small, medium, and large effects were 0.01, 0.06, and 0.14 for partial eta squared [η_p^2] and 0.2, 0.5, and 0.8 for Cohen’s [d], respectively (Fritz et al., 2012). The relationships were analyzed with a two-tailed Pearson’s correlation [$\nu_{La,max} (t_{PCr -3.5\%})$ vs. $P^{\nu}_{La,max}$, $\nu_{La,max} (t_{PCr-peak})$ vs. $P^{\nu}_{La,max}$, and W_{mean} and W_{Gly} vs. different $\nu_{La,max}$]. The Bland–Altman plots were determined to analyze the bias, difference, average, and 95% limit agreements among the $\nu_{La,max} (t_{PCr -3.5\%})$, the $\nu_{La,max} (t_{PCr-peak})$, and the $P^{\nu}_{La,max}$ (Bland and Altman, 1995).

Results

Energetic contributions during 15-s ASCT

The repeated-measures ANOVA indicated significant differences in energetic contributions in kilojoules and their percentages ($p < 0.0001$, effect size [η_p^2]: 0.90; $p < 0.0001$, [η_p^2]: 0.98, respectively). The value of W_{PCr} was significantly higher than that of W_{Gly} and W_{Oxi} in kilojoules as well as in percentage ($p < 0.0001$, [d]: 1.45, 2.96, and 5.13 in kJ; $p < 0.0001$, [d]: 3.53, 7.72, and 4.37 in percentage, respectively) (Figure 2A).

Physiological parameters and relationships between different calculations of $\nu_{La,max}$

The time duration (s) of the $\nu_{La,max}$ -related $t_{PCr -3.5\%}$ was significantly higher than $t_{PCr-peak}$ ($p < 0.0001$, [d]: 1.42; Table 1).

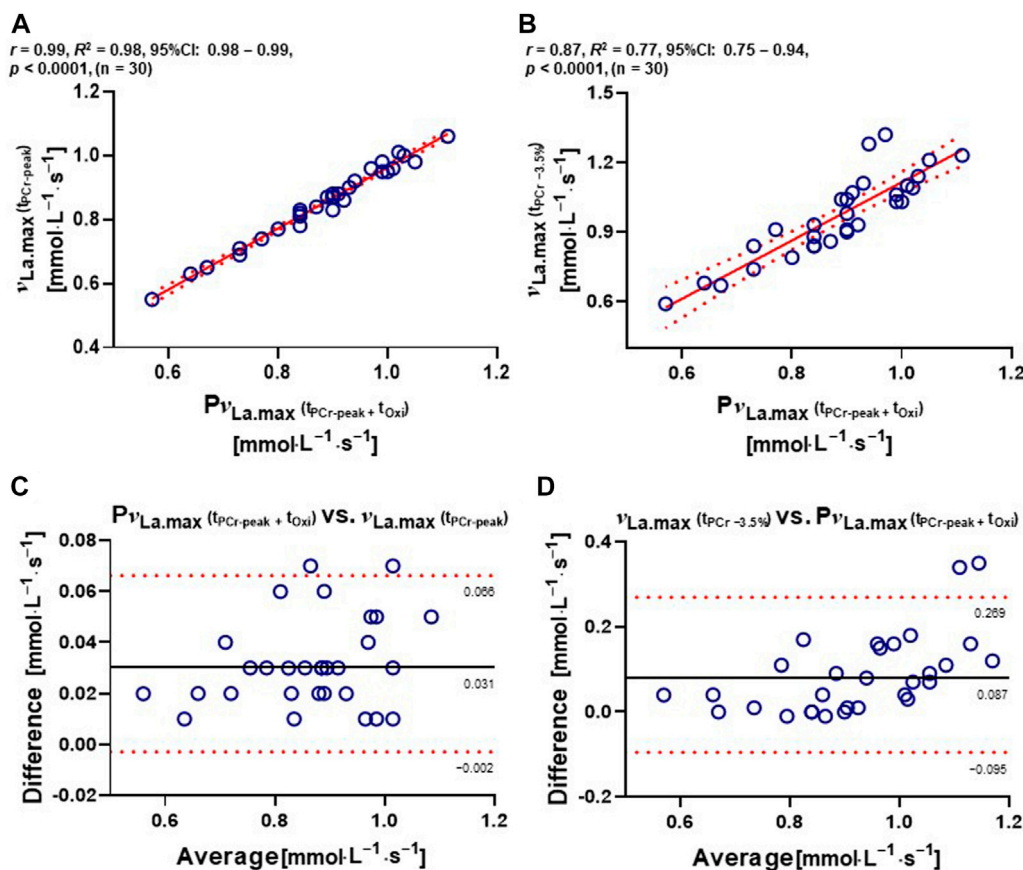


FIGURE 3

Relationships and Bland–Altman plots between different calculations of $v_{La,max}$. (A) Two-tailed Pearson’s correlation between $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$). (B) Two-tailed Pearson’s correlation between $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-3.5\%}$). (C and D) Bland–Altman plots of differences between $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$) and between $v_{La,max}$ ($t_{PCr-3.5\%}$) and $P v_{La,max}$. The dashed line represents bias. The dotted line represents 95% limit of agreements. CI, confidence interval; ES, effect sizes; $v_{La,max}$, maximal rate of lactate accumulation; $P v_{La,max}$, pure maximal rate of lactate accumulation; t_{Oxi} , time of oxidative energy system contribution; $t_{PCr-peak}$, phosphagen energy system–contributed time until the peak power output; $t_{PCr-3.5\%}$, phosphagen energy system contributed –3.5% time point from the peak power output. Significant difference; **** $p < .0001$.

0.092. $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$) calculations indicated a smaller 95% limit of agreement (–0.002 to 0.066) followed by $v_{La,max}$ ($t_{PCr-3.5\%}$) and $P v_{La,max}$ (–0.095 to 0.269) (Figures 3C, D).

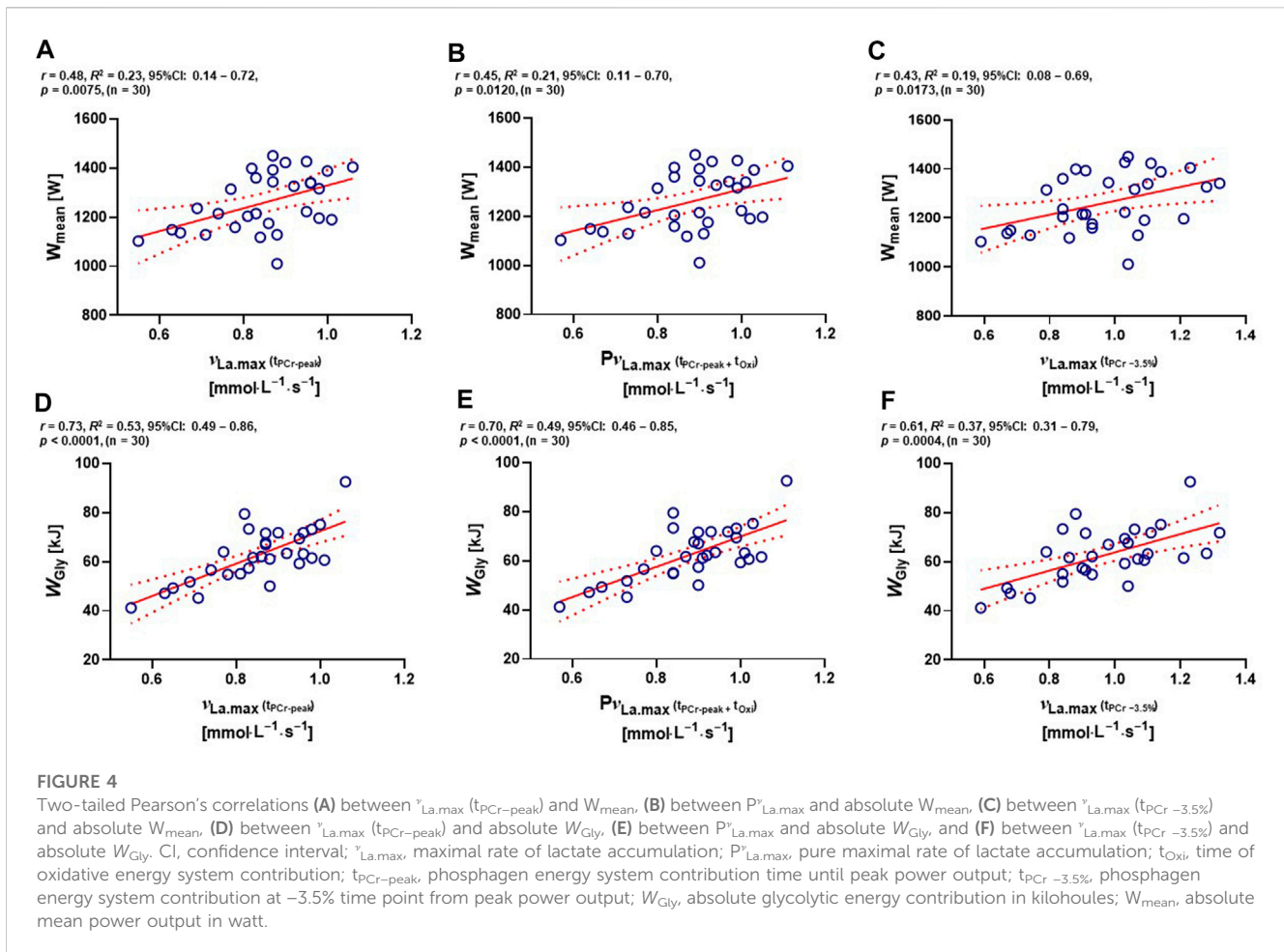
Relationships between anaerobic performance and different $v_{La,max}$

Low positive correlations between $v_{La,max}$ ($t_{PCr-peak}$) and absolute W_{mean} , $P v_{La,max}$ and absolute W_{mean} , and $v_{La,max}$ ($t_{PCr-3.5\%}$) and absolute W_{mean} were observed ($r = 0.48$, $R^2 = 0.23$, 95% CI: 0.14–0.72, and $p = 0.0075$; $r = 0.45$, $R^2 = 0.21$, 95% CI: 0.11–0.70, and $p = 0.0120$; $r = 0.43$, $R^2 = 0.19$, 95% CI: 0.08–0.69, and $p = 0.0173$, respectively) (Figures 4A–C). Furthermore, moderate to high positive correlations between $v_{La,max}$ ($t_{PCr-peak}$) and W_{Gly} , $P v_{La,max}$ and W_{Gly} , and $v_{La,max}$ ($t_{PCr-3.5\%}$) and W_{Gly} in kilojoules were found ($r = 0.73$, $R^2 = 0.53$, 95% CI: 0.49–0.86, and $p < 0.0001$; $r = 0.70$, $R^2 = 0.49$, 95% CI: 0.46–0.85, and $p < 0.0001$; $r = 0.61$, $R^2 = 0.37$, 95% CI: 0.31–0.79, and $p = 0.0004$, respectively) (Figures 4D–F).

Discussion

In previous studies, calculations of $v_{La,max}$ for the maximal glycolytic capacity after the 15-s ASCT were limited because t_{PCr} and aerobic energy contribution were not considered. To the best of our knowledge, this study is the first to integrate the oxidative energy contribution and contributions of the three energy systems during the 15-s ASCT via a modified $P v_{La,max}$ calculation. This modified $P v_{La,max}$ was compared with previous $v_{La,max}$ calculations for glycolytic performance and their correlations were determined.

The main findings of this study confirm that phosphagen and glycolytic systems are predominantly utilized, while the oxidative energy metabolism contributes to $3.13\% \pm 1.61\%$ during the 15-s ASCT. The $t_{PCr-peak}$ and t_{Oxi} -subtracted $P v_{La,max}$ values were lower than $v_{La,max}$ ($t_{PCr-3.5\%}$) but higher than $v_{La,max}$ ($t_{PCr-peak}$) values. Moreover, very strong and high correlations between $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-peak}$) and between $P v_{La,max}$ and $v_{La,max}$ ($t_{PCr-3.5\%}$) were found. Three different $v_{La,max}$ values were positively associated with absolute W_{mean} and W_{Gly} values.



The phosphagen energy system has the highest absolute energetic contribution during the 15-s ASCT, followed by glycolytic and oxidative energy metabolism, thus being in agreement with the results of a previous study by Park et al. (2021). In this study, all three energy systems were analyzed using the same PCr-La⁻O₂ method during a 100-m sprint and the oxidative energy system contributed over 10% here to the total energy requirements. In comparison to this outcome, the oxidative contribution in the present study was lower (~3%) during the 15-s ASCT (Figure 2A). These different results might be because 100-m sprint and sprint cycling are differently characterized by maximal anaerobic performances, which include different movements of the upper extremities. Previous studies have reported that smaller muscles such as those in the upper extremities do not significantly contribute to total lactate accumulation (Julio et al., 2017; Yang et al., 2022b). Therefore, glycolytic energy contribution during the 15-s ASCT likely had a higher percentage (35% ± 7%) than during a 100-m sprint (~25 ± 7%) as obtained in a previous study outcome (Park et al., 2021), which in turn reduced the relative oxidative contribution.

Regarding the different calculations of $\dot{V}_{La,max}$, the level of $\dot{V}_{La,max} (t_{PCr-3.5\%})$ showed significantly higher values than $\dot{V}_{La,max} (t_{PCr-peak})$ and $P^{\dot{V}}_{La,max}$ (Figure 2B) because the $t_{PCr-3.5\%}$ value calculated was 3.2 ± 1.0 s during the 15-s ASCT (Table 1) such that the denominator (Δ time) of the formula was smaller than the others.

Due to the same reason, in including $t_{PCr-peak} + t_{Oxi}$, $P^{\dot{V}}_{La,max}$ showed higher values than $\dot{V}_{La,max} (t_{PCr-peak})$. According to our results, the calculation of $\dot{V}_{La,max} (t_{PCr-3.5\%})$ was unsuitable to determine the glycolytic capacity or $\dot{V}_{La,max}$ because the determined t_{PCr} time of -3.5% from W_{peak} was based on an error of the early SRM cycle ergometer (Weber, 2003). On the other hand, previous researchers suggested no lactate production during t_{PCr} which was incorrectly (fictitiously) assumed (Heck et al., 2003; Hauser et al., 2014; Adam et al., 2015; Nitzsche et al., 2018; Quittmann et al., 2020; Quittmann et al., 2021). In this regard, it is well known that all three energy systems start to work simultaneously and lactate production occurs independently of O₂ availability such as under anoxic, hypoxic, and normoxic conditions (Gastin, 2001; Philp et al., 2005; Brooks, 2018; Yang et al., 2020; Brooks et al., 2022; Yang et al., 2022b). La⁻ might be accumulated at a relatively low level during the initial seconds of the 15-s ASCT because ATP-PCr is a dominant energy contribution until the achievement of W_{peak} (Serresse et al., 1988; Beneke et al., 2002; Park et al., 2021). Moreover, Heck et al. (2003) have suggested that aerobic power and contribution are of minor significance during maximal short-term exercise testing. However, this interpretation is based on the results of a computer simulation that originated from systems biology (Wackerhage et al., 2022). The calculated $\dot{V}_{La,max}$ values with and without t_{Oxi} show significant differences in our study's outcomes (Table 1; Figure 2B). Therefore, oxidative metabolism should be

considered when aiming to analyze a pure maximal glycolytic rate. Considering the abovementioned factors, the accuracies of $\dot{V}_{La,max}$ ($t_{PCr-peak}$) and $P_{La,max}^v$ calculations seem to be higher because the durations of $t_{PCr-peak}$ and t_{Oxi} are additionally involved in calculating formulas by subtracting them from the total exercise time. Accordingly, $P_{La,max}^v$ was very strongly correlated with $\dot{V}_{La,max}$ ($t_{PCr-peak}$), and this correlation was higher than that of $P_{La,max}^v$ with $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$). The Bland–Altman plot between $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-peak}$) also showed a smaller limit of agreement than the limit of agreement between $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$) and $P_{La,max}^v$ (Figures 3C, D). Furthermore, $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-peak}$) were associated with absolute W_{mean} and W_{Gly} . Such associations were higher than those of $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$), with absolute W_{mean} and W_{Gly} (Figures 4A–F). These results indicate that $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-peak}$) are better calculating methods for glycolytic capacity/power.

To determine the anaerobic performance, the 30-s Wingate anaerobic test is often used in related studies (Bar-Or, 1987; Gastin, 2001; Zupan et al., 2009; Jaafar et al., 2014). However, this time frame will likely increase the oxidative contribution to the total energy demand and may also lead to an inhibition of phosphofructokinase activity because of accumulated hydrogen ions from increased ATP hydrolysis and reduced pH-levels (Gastin, 2001; Heck et al., 2003; Robergs et al., 2004; Yang et al., 2022b). This increased oxidative contribution may then reduce lactate accumulation and increase lactate elimination, which results in a reduced likelihood of measuring the maximal lactate accumulation (Heck et al., 2003; Yang et al., 2020; Yang et al., 2022b; Wackerhage et al., 2022). Thus, the $\dot{V}_{La,max}$ determination combining the 15-s ASCT with the $P_{La,max}^v$ formula using the PCr-La⁻O₂ method is more suitable to limit the activation of oxidative metabolism as much as possible in decreasing intracellular lactate oxidation (Heck et al., 2003; Wackerhage et al., 2022).

In the current study, the levels of $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$) were higher than those of $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-peak}$), while a very strong relationship between $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-peak}$) was observed, one that was better than the relationship between $P_{La,max}^v$ and $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$). Therefore, the calculation of $P_{La,max}^v$ using the analysis of energetic contributions should be considered in scientific research to precisely analyze the maximal rate of lactate accumulation and anaerobic capacity/power. In practical diagnostics, the calculation of $\dot{V}_{La,max}$ ($t_{PCr-peak}$) may be useful without a complicated analysis of energetic contributions or if it is not possible to be available for gas analyzer equipment eventually. Otherwise, the use of $\dot{V}_{La,max}$ ($t_{PCr-3.5\%}$) calculation is only suggested if the early version of the SRM cycle ergometer is available to perform the 15-s ASCT.

This study successfully identified the differences of three possible $\dot{V}_{La,max}$ calculations during the 15-s ASCT. However, the current study has some limitations. Because a spiroergometry system processing a dynamic micro-mixing chamber mode was not available during the test, the $\dot{V}O_2$ data were measured with the breath-by-breath method using a portable gas analyzer during the 15-s ASCT, which was converted to calculate W_{Oxi} . This measurement mode during a maximal effort exercise has some errors (2–4%, approximately). Thus, the outcomes might be influenced by this factor. Moreover, although the $t_{PCr-peak}$ determination is the physiologically acceptable method using the peak power output in sports

science, the direct measuring of t_{PCr} is very difficult or impossible. It has never been measured using biomarkers/sensors such as the isotopic tracers or fluorescent protein sensors during a maximal short-term effort in humans. Actual direct measurements for t_{PCr} and exact metabolic contributions have to be determined in future studies. Further studies might also have to develop sport-specific $P_{La,max}^v$ testing in other high-intensity intermittent sports disciplines such as football, handball, basketball, rugby, and combat sports as anaerobic performance profiling.

Regarding the possible gender differences in energetic contributions, Yang et al. (2022a) recently calculated the energy system contributions during increasing exercise intensities. The results found different W_{PCr} and W_{Gly} levels between males and females that were attributed to the differences in skeletal muscle mass and all fiber types. Therefore, there may be a need for further research into gender differences in the $P_{La,max}^v$ calculation. Furthermore, the distribution of muscle fiber types might be considered when interpreting high or low $\dot{V}_{La,max}$ values in individual athletes with higher muscle mass and more glycolytic type IIA and IIX fibers who show generally higher lactate production during aerobic and anaerobic exercises (Ivy et al., 1980; Wackerhage et al., 2022). Future studies must show to what extent $\dot{V}_{La,max}$ might shift during a training year in track athletes with a different $\dot{V}_{La,max}$.

Moreover, there are currently no clear data available about which specific individual training sessions are helpful in improving $\dot{V}_{La,max}$. A recent study by Schünemann et al. (2023) suggests that sprint training, resistance training, and hypoxic training may increase glycolytic capacity and anaerobic performance. However, direct interventional approaches related to improving maximal glycolytic metabolism as $P_{La,max}^v$ should be investigated further.

Conclusion

The findings of the current study indicate that a modified calculation of $P_{La,max}^v$ with the additional incorporation of further energetic contributions is precision enhancing and therefore valuable for determining the maximal glycolytic rate or $\dot{V}_{La,max}$. Our modified calculation therefore allows for a more detailed input of individual characteristics of energy metabolism to becoming an increasingly popular method for determining differences in maximal rates of lactate accumulation. In light of inter-individual differences in maximal force generation, phosphagen levels, and oxidative capacity, our method allows for compensating this interaction during $\dot{V}_{La,max}$ measurements when compared to previous methods. According to our results, the calculated formula of $P_{La,max}^v$ should be used for scientific research in exercise sciences to determine the maximal anaerobic capacity/power more precisely and with the exclusion of the aerobic component. This is supported by a small limit of agreement (a small variation) and very high correlation with $\dot{V}_{La,max}$ ($t_{PCr-peak}$). Furthermore, the calculation of $\dot{V}_{La,max}$ ($t_{PCr-peak}$) might be recommended for a faster analysis of the practical approach in the field.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving human participants were reviewed and approved by the Institutional Review Board of CHA University, along with this study (No. 1044308-202206-HR-032-02). The patients/participants provided their written informed consent to participate in this study.

Author contributions

W-HY, S-YP, TK, H-JJ, OH, and SG were involved in the conception and design of the research. W-HY, S-YP, TK, and H-JJ collected the data. W-HY and S-YP analyzed the data. W-HY wrote the first draft of the manuscript. W-HY, OH, and SG revised and edited the manuscript. All authors approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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