International Journal of Sports Science and Physical Education
2026, Vol. 11, No. 1, pp. 1–10
https://doi.org/10.11648/j.ijsspe.20261101.11

Research Article

Validity of the Calculated VO_{2max} from Cycling Power and VLamax

Reinout Van Schuylenbergh*, Asatur Khurshudyan, Sebastian Weber

Research Department, INSCYD GmbH, Salenstein, Switzerland

Abstract

Current VO_{2max} assessment methodologies are based on the usage of expensive ergospirometry devices. Available statistical models neglect the individual's metabolic characteristics and show low accuracy. We investigated the validity of INSCYD software to calculate VO_{2max} from the power output at all-out cycling efforts, body weight, fat percentage and VLamax as an alternative to ergospirometry. Eleven trained male volunteers performed six maximal cycling tests of 20s to ~12 min duration. INSCYD software was used to model the metabolism during the tested efforts and to calculate VO_{2max}. The calculated VO_{2max} was compared with the measured VO_{2max} with ergospirometry during the ramp test and the 3- and 6-min maximal efforts. Excellent agreement was achieved between the calculated and measured VO_{2max} (*ramp*: Δ-0.21 $ml \cdot min^{-1} \cdot kg^{-1}$, Δ95%CI: -2.46 to 2.0 $mL \cdot min^{-1} \cdot kg^{-1}$; *3min*: Δ-1.35 $ml \cdot min^{-1} \cdot kg^{-1}$, Δ95%CI: -3.04 to 0.33 $mL \cdot min^{-1} \cdot kg^{-1}$; *6min*: Δ0.34 $mL \cdot min^{-1} \cdot kg^{-1}$, Δ95%CI: -1.01 to 1.68 $mL \cdot min^{-1} \cdot kg^{-1}$). A valid VO_{2max} can be obtained from the power data of 2 maximal efforts of 3- and 6-min duration and a sprint test to calculate VLamax. This procedure can be implemented in the normal training regimen of athletes, without the need for expensive equipment. Future research should focus on testing the validity of the model on larger samples including females.

Keywords

$\dot{V}O_{2max}$, VLamax, Cycling, Cycling Power

1. Introduction

The maximal oxygen uptake ($\dot{V}O_{2max}$) is the highest rate of oxygen (O_2) that can be used by the human body. It represents the integrated ability of the pulmonary, cardiovascular and muscle systems to take up, transport and utilize O_2. The maximal oxygen uptake is widely accepted as an indicator of the system's ability to deliver oxygen to the active muscle as well as a biomarker of health. Maximal oxygen uptake and its clinical correlate cardiorespiratory fitness are key determinants of both performance in endurance sports [1-3], mortality in the general population [4, 5] and quality of life at old age [6]. Values can be as high as ~80 $mL \cdot min^{-1} \cdot kg^{-1}$ in female and ~95 $mL \cdot min^{-1} \cdot kg^{-1}$ in male elite endurance athletes [7, 8] and as low as 35-45 $mL \cdot min^{-1} \cdot kg^{-1}$ in healthy, non-trained adults of similar age and gender [9]. Individuals with a cardiorespiratory fitness level <5 METs (1 MET ≅ 3.5 $ml \cdot min^{-1} \cdot kg^{-1}$) tend to have a particularly high risk for mortality, whereas many epidemiological studies have observed that cardiorespiratory fitness levels >8 to 10 METs are associated with relative protection [5].

*Correspondence: Reinout Van Schuylenbergh (Reinout@inscyd.com)

Received: 5 February 2026; **Accepted:** 14 February 2026; **Published:** 27 February 2026

Increasing $\dot{V}O_{2max}$ is an important training objective to improve athletic performance, cardiorespiratory fitness and life expectancy [10]. For instance, an increase of $\dot{V}O_{2max}$ with 1 MET increases life expectancy with 10-25% [5]. Overwhelming scientific data demonstrates that previously untrained humans will respond to endurance exercise training provided the stimulus is sufficient. For instance, in the Heritage Family Study 633 sedentary individuals were assigned to 20 weeks of exercise training three times a week, 55-75% of $\dot{V}O_{2max}$ for 30-50 min. The maximal oxygen uptake improved by 17±9% [11]. Similar training effects are not limited to untrained subjects. Also endurance trained subjects can increase $\dot{V}O_{2max}$. Odden et al observed an 8±4.3% increase in $\dot{V}O_{2max}$ after 9 weeks of endurance training in already well-trained cyclists ($\dot{V}O_{2max}$ 65.1±5.3 $mL \cdot min^{-1} \cdot kg^{-1}$) [12].

To assess the individual's training and health status, adequate monitoring should be performed at regular intervals [5]. Gold standard procedures for $\dot{V}O_{2max}$ assessment include ergospirometry during maximal ramp or time trial testing [13-15]. Such methods require trained personnel, specific and expensive equipment (e.g. Ergospirometry systems) and are prone to measurement errors [16, 17], hence limiting its practical useability. To improve accessibility, self-paced short-duration maximal efforts have been suggested as a valid and practical alternative for the determination of $\dot{V}O_{2max}$ [18]. Although such tests show strong correlations to the measured $\dot{V}O_{2max}$ ($R^2 = 0.71$) [18], large errors may occur in the individual (differences between calculated and measured $\dot{V}O_{2max}$ up to 10 $ml \cdot min^{-1} \cdot kg^{-1}$). Such errors exceed the expected changes in $\dot{V}O_{2max}$ as a result of e.g. 7-12 weeks high-intensity endurance training [12, 19, 20]. Likely, these errors can be attributed to the individual differences in the anaerobic energy contribution for such short-duration maximal efforts. For instance, in a 5 min maximal effort 10-20% of the energy requirements may come from anaerobic metabolism [21]. In this reasoning, accounting for the anaerobic energy contribution might improve $\dot{V}O_{2max}$ assessments from short-duration maximal efforts. Recently, the maximal lactate production rate (VLamax) as a proxy for the maximal glycolytic power has attracted interest in the scientific community [22, 23], although the metric is not new as it dates back to the work of Mader and Heck [24-26]. As the glycolytic energy contribution during longer durations is a function of maximal glycolytic power [25, 27], including VLamax in a prediction model for $\dot{V}O_{2max}$ determination might improve the accuracy of currently available models based on power output data. Hence, this study investigates the validity of a popular commercial algorithm for $\dot{V}O_{2max}$ calculation based on cycling power data and the VLamax. As VLamax assessments from sprint tests are sensitive to the applied protocol [28, 29], we investigate the effect of three different sprint protocols on the accuracy of the $\dot{V}O_{2max}$ predictions.

2. Materials and Methods

2.1. Subjects

Eleven endurance-trained male subjects (mean±SD: age 32.2±15.2 y, mass 70.9±6.7 kg, height 180.4±6.6 cm, body fat 14±5.6%, $\dot{V}O_{2max}$ 4.09±0.5 $L \cdot min^{-1}$, VLamax 0.48±0.09 $mmol \cdot L^{-1} \cdot s^{-1}$) provided informed written consent to participate in the study. All subjects were experienced with laboratory exercise testing on the cycle ergometer as a part of their normal training routine. The study protocol was performed according to the ethical standards of the Declaration of Helsinki. The study received ethical approval by the ethics committee of the Hildesheim University, Germany.

2.2. Test Procedures

The subjects performed three laboratory visits over a two-week period. They completed a ramp test and six maximal performance tests of 20 sec to 6 min duration (Figure 1). The test durations were specifically selected to assess VLamax (20s sprint tests) [30] and $\dot{V}O_{2max}$ (3 to 12 min maximal endurance tests) [15]. The day before the experiments exercise was restricted to maximum 1 hour of low-intensity training. Furthermore, the subjects were instructed to consume ~3h before the experiments a standardized meal (~2700 kJ; 71% carbohydrate, 15% fat, 14% protein). To avoid fluctuations of the subject's initial muscle glycogen content, identical training and food regimen for all subsequent experimental sessions were implemented [31]. To control for potential diurnal variation, subjects completed the experimental exercise sessions at the same time of the day across trials. All cycling tests were conducted using each subject's personal racing bike mounted on a calibrated cycle ergometer (Cyclus 2, Leipzig, Germany). The Cyclus 2 is an electromagnetically braked ergometer. The Cyclus 2 ergometer measures power output with an accuracy error of ±2% according to the manufacturer (www.cyclus2.com). The gear ratio was fixed at either 53 x 12 or 52 x 12, depending on the front chainring of the subject's bicycle. The cycling tests were performed in an air-conditioned exercise laboratory (19 ℃, 60% relative humidity) and supervised by trained personnel. The subjects received standardized verbal encouragement to ensure maximal effort during all exercise tests. During all tests, external airflow was provided to facilitate thermoregulation [32].

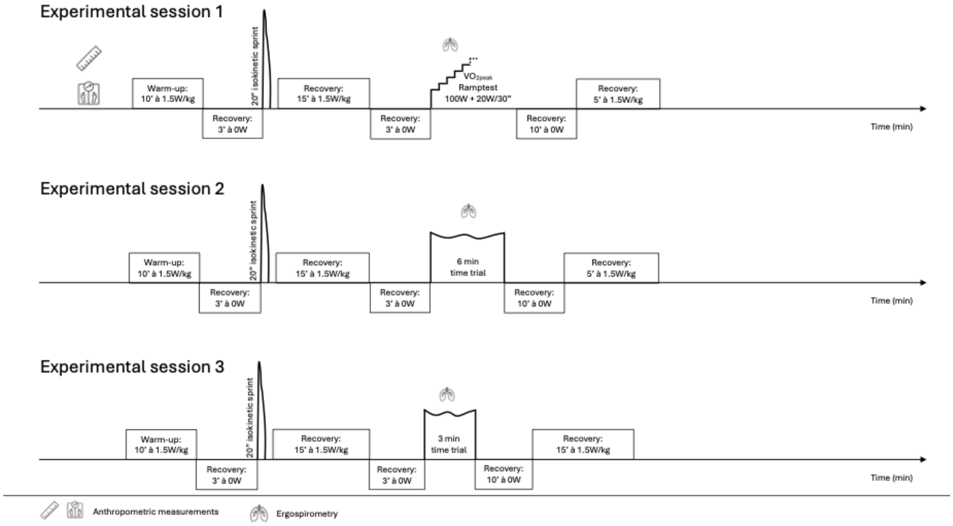

Figure 1. *Study design.*

2.2.1. Experimental Session 1

At the first visit to the laboratory, the subject's body length, body mass and body composition (Seca, BCA 525, Hamburg Germany) were measured. After these measurements, the subject cycled during 10 min at 1.5 W·kg^{-1} at a self-selected cadence. This warm-up phase was extended by 3 min of passive recovery to reduce the aerobic energy contribution in the subsequent sprint.

The first test consisted of a 20s isokinetic sprint at 120 rev·min^{-1} in a seated position. The initial load of the ergometer was set at three times the fat free mass of the subjects (in Newton) with the isokinetic mode ~~was~~ activated at 60 rev·min^{-1} (SPR1). Thereafter, the subjects cycled for minimum 15 min at 1.5 W·kg^{-1} to promote recovery between the tests. The recovery status was monitored by measuring the blood lactate concentration (BLC) (EKF, Biosen C-line, Barleben, Germany). If ~~Subjects with~~ BLC remained above 2 mmol·L^{-1}, the active recovery was extended by 3 min.

After the sprint-test a ramp protocol was performed to assess $\dot{V}O_{2max}$. The test started at 100 W and increased by 20 W every 30s until volitional exhaustion. The subjects were allowed to use their preferred cadence (97±7 rev·min^{-1}). Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were fully captured in a grander airstream and measured continuously (Omnical Sport, Maastricht Instruments, The Netherlands) [33]. Heart rate was recorded with a conventional chest strap (Polar, Kempele, Finland). The highest 30s moving average $\dot{V}O_2$ was used to establish $\dot{V}O_{2max}$ [34]. A maximal effort was achieved when a $\dot{V}O_2$ plateau was observed ($\dot{V}O_2$ increase < 120 mL·min^{-1} despite an increase in workload) or when 2 or more of the following criteria were met [35]:

1) Maximal heart rate within 10 beats of the age predicted maximal heart rate (220-age)
2) RER > 1.1
3) BLC > 8.0 mmol·L^{-1}

2.2.2. Experimental Session 2

During the second laboratory visit, the subjects completed an identical warm-up as described in experimental session 1. Following the warm-up, the subjects performed a 20s isokinetic sprint. The initial resistance was set at the fat free mass of the subjects (in Newton) with the isokinetic mode activated at 80 rev·min^{-1} (SPR2). Subsequently, a minimum of 15 min of active recovery at 1.5 W·kg^{-1} was performed to facilitate recovery between the tests. The recovery status was monitored via BLC; if-BLC remained above 2 mmol·L^{-1}, the active recovery was extended by 3 min. Finally, the subjects performed a 6 min maximal time trial (TT_6), with instructions to maintain the highest possible average power output throughout the duration of the test. The subjects could adjust the workload intensity (5-W steps) at any time. The subject performed the test in the seated position. They used the same pedaling frequency as from the ramp test (experimental session 1). Breathing gases were analyzed (Omnical Sport, Maastricht Instruments, The Netherlands) and heart rate recorded (Polar, Kempele, Finland).

2.2.3. Experimental Session 3

During the third laboratory visit, the subjects performed an identical warm-up as described in experimental session 1 and 2. Following the warm-up, the subjects completed a 20s isokinetic sprint and a 3 min maximal time trial. The sprint was performed in similar experimental conditions as the sprints in experimental session 1 and 2, although the initial load was set at five times the fat free mass of the subjects (in Newton) and the isokinetic mode was activated at 20 rev·min^{-1} (SPR3). The 3 min time trial followed identical procedures as described for the 6 min time trial (experimental session 2).

2.3. Calculating $\dot{V}O_{2max}$ and VLamax

Based on the measured power data (8Hz) from the isokinetic sprints, TT_3 and TT_6, the $\dot{V}O_{2max}$ and VLamax were calculated using a commercially available software (INSCYD physiological performance software, version 3.0, INSCYD GmbH, Salenstein, Switzerland). The calculations in the software are built on evolutions of mechanistic models of muscle metabolism and cardiopulmonary kinetics which to a great extend originated from published as well as unpublished work from Mader [36, 37].

Individual data used to run these calculations were: sex, body mass, body fat percentage and the power data from TT_3, TT_6 and the sprint tests. All other settings in the software were kept at default values as preset in the software. The software's algorithm detects the glycolytic energy production from the sprint power data, accounting for the energy contribution from phosphocreatine and oxidative phosphorylation and calculates VLamax from this analysis. The power data from the 3- and 6-min time trial allow for the calculation of the $\dot{V}O_2$ kinetics of the efforts, including the fast and slow $\dot{V}O_2$ of these efforts. The average peak $\dot{V}O_2$ from these two efforts is taken as the calculated $\dot{V}O_{2max}$.

2.4. Statistical Analysis

Raw data was processed using Microsoft Excel (version 16.92, Redmond, USA). The Shapiro Wilk test was employed to assess the normality of the data. Descriptive statistics were calculated for all variables, with the data presented as mean ± standard deviation (SD). Pearson correlations were determined between the calculated $\dot{V}O_{2max}$ and the measured $\dot{V}O_{2max}$ from the ramp test, TT_3 and TT_6. Correlation coefficients less than 0.5, between 0.5 and 0.75, between 0.75 and 0.9 and greater than 0.9 are indicative of poor, moderate, good and excellent correlation, respectively [38].

A one-way ANOVA for repeated measures was performed to test significant differences between the calculated $\dot{V}O_{2max}$ and the measured $\dot{V}O_{2max}$ from the ramp test, TT_3 and TT_6. Holm post-hoc analysis was performed where appropriate.

A one-way ANOVA for repeated measures (sprint 1 to 3) was performed to test significant differences between the VLamax values calculated from the 3 sprints. Holm post-hoc analysis was performed where appropriate.

Bland Altman analyses (expressed as the mean±1.96SD) were used to quantify the bias and the range of agreement between the calculated $\dot{V}O_{2max}$ and the measured $\dot{V}O_{2max}$ from the ramp test, TT_3 and TT_6. If the confidence interval (Δ95%CI) was less than ±2.5 $ml \cdot min^{-1} \cdot kg^{-1}$, the calculated $\dot{V}O_{2max}$ was considered in agreement and therefore interchangeable [39].

A probability level of $p < 0.05$ was set as the criterion for acceptance of statistical significance. Statistical analyses were performed using JASP statistical software (version 0.95.4 for Apple Silicon, Amsterdam, The Netherlands).

3. Results

3.1. VLamax Calculations

VLamax and average sprinting power were not affected by the test condition (ergometer settings) (Table 1). Peak sprint power was ~11% higher in the sprint condition starting from a higher cadence (80 $rev \cdot min^{-1}$), compared to the sprint from a lower cadence (20 $rev \cdot min^{-1}$).

Table 1. *Average power output (PO), BLCpre, BLCpost and VLamax for the isokinetic sprint tests. Mean±SD.*

	SPR1	SPR2	SPR3
Peak PO (W)	970±188	1014±181 ^{c}	913±179 ^{b}
Average PO (W)	709±91	696±89	730±94
VLamax ($mmol \cdot L^{-1} \cdot s^{-1}$)	0.48±0.09	0.48±0.09	0.48±0.09

Repeated measures ANOVA: ^{a} different from SPR1; ^{b} different from SPR2; ^{c} different from SPR3 ($p<0.05$).

3.2. $\dot{V}O_{2max}$ Calculations

During the ramp test, a $\dot{V}O_2$ plateau was observed in 4 subjects (~36%). All subjects met the criteria for exhaustion. The measured $\dot{V}O_{2max}$ ranged between 57.2±8.6 and 58.6±9.1 $mL \cdot kg^{-1} \cdot min^{-1}$, without significant differences between the test conditions. The calculated $\dot{V}O_{2max}$ amounted 58.3±9.4 $mL \cdot kg^{-1} \cdot min^{-1}$.

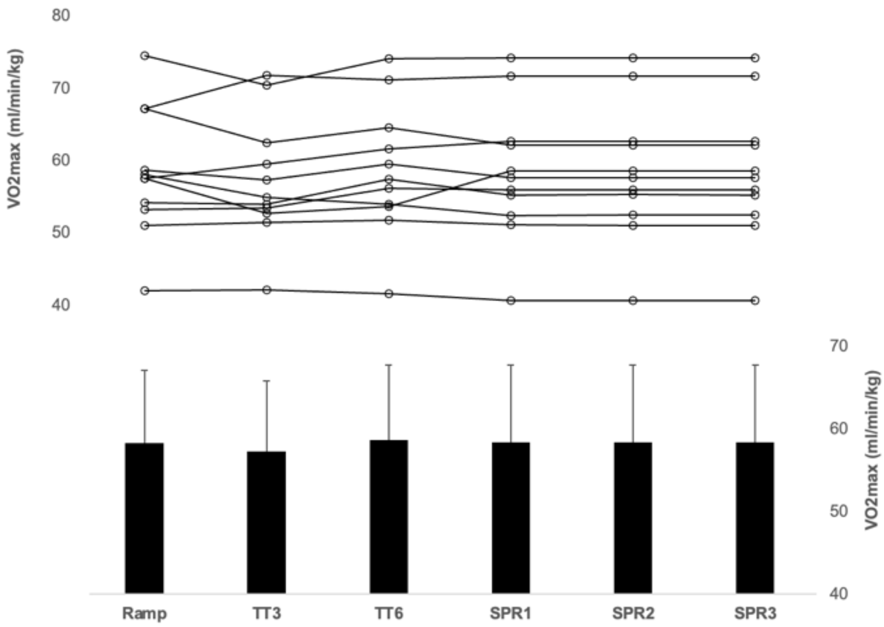

*Figure 2. Maximal oxygen consumption ($\dot{V}O_{2max}$). Measured (Ramp, TT3, TT6) and calculated values (based on the power data from TT3, TT6 and SPR1-3) – (see methods for more details). Open circles represent the individual data; the black bars represent the mean±SD. * Different from Ramp (p< 0.05 repeated measures ANOVA).*

Pearson correlation's revealed excellent correlations between the measured and the calculated $\dot{V}O_{2max}$ values (0.93 – 0.98, $p<0.05$) (Figure 3).

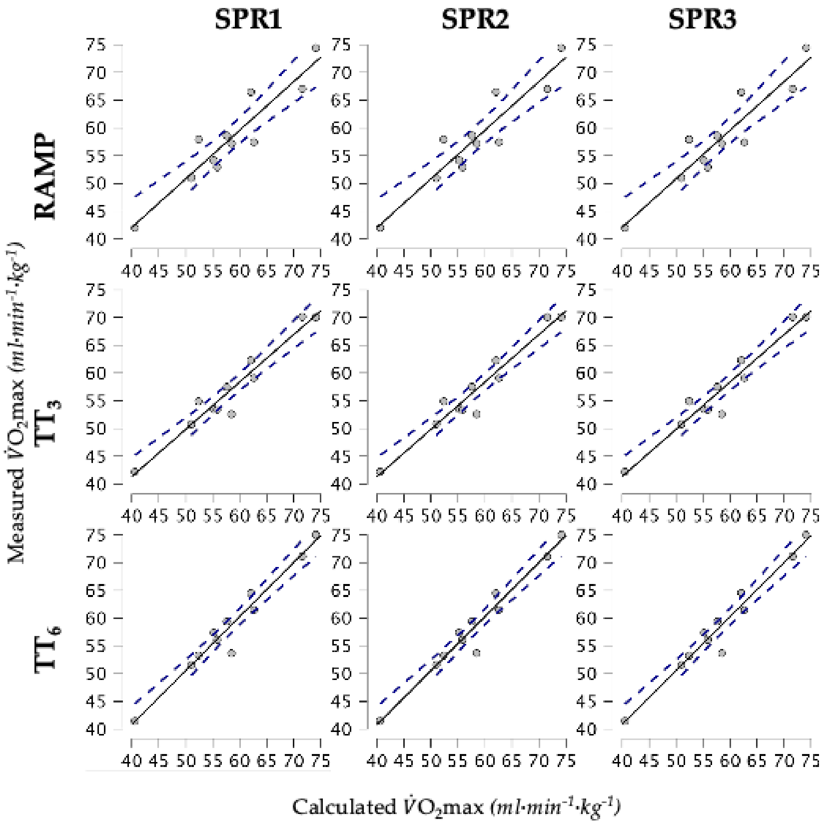

Figure 3. Pearson correlation coefficients for the maximal oxygen uptake. Comparison of the measured (Ramp, TT_3, TT_6) and the calculated values (based on the power data from TT_3, TT_6 and SPR1-3). (see methods for more details). All Pearson correlations ($p<0.001$).

Bland Altman analyses between measured and calculated $\dot{V}O_{2max}$ are presented in Table 2. The graphical representation of this analysis is available in appendix A. The smallest bias was observed for the comparison with the ramp test (Δ = –0.21 mL·min^{-1}·kg^{-1}; 95% CI: –2.46 to 2.00 mL·min^{-1}·kg^{-1}). The bias relative to TT_6 was slightly larger (Δ = 0.34 mL·min^{-1}·kg^{-1}; 95% CI: –1.01 to 1.68 mL·min^{-1}·kg^{-1}). In contrast, the calculated $\dot{V}O_{2max}$ overestimated the measured $\dot{V}O_{2max}$ from TT_3 by 1.35 mL·min^{-1}·kg^{-1}.

Table 2. *Bland Altman analyses.*

		Ramp	**TT_3**	**TT_6**
		Calculated versus measured $\dot{V}O_{2max}$ (mL min^{-1} kg^{-1})		
SPR1	Bias LoA *Δ95% CI*	-0.21 -6.77, 6.36 *-2.46, 2.0*	-1.35 -6.26, 3.55 *-3.04, 0.33*	0.34 -3.58, 4.26 *-1.01, 1.68*
SPR2	Bias LoA *Δ95% CI*	-0.22 -6.77, 6.33 *-2.46, 2.03*	-1.36 -6.26, 3.54 *-3.04, 0.32*	0.33 -3.58, 4.24 *-1.01, 1.67*
SPR3	Bias LoA *Δ95% CI*	-0.21 -6.76, 6.34 *-2.46, 2.04*	-1.36 -6.26, 3.55 *-3.04, 0.33*	0.34 -3.59, 4.26 *-1.01, 1.68*

Bland Altman analyses: Bias, limits of agreement (LoA) and 95% Confidence intervals (Δ95% CI).

4. Discussion

The purpose of this study was to investigate the accuracy of the $\dot{V}O_{2max}$ assessments from maximal cycling power and $\dot{V}$Lamax data. According to our observations, INSCYD software provide accurate calculations of the $\dot{V}O_{2max}$ from these data sources. To the best of our knowledge, our study was only the second study to test the validity of INSCYD software for $\dot{V}O_{2max}$ assessment. Our data is in line with the observations of Podlogar et al [40] although they used a different test protocol including lactate tests, whereas in the current study only power data has been used. They investigated the validity of the INSCYD software in a cohort of trained cyclists ($\dot{V}O_{2max}$ 61±7.9 mL·min^{-1}·kg^{-1}). Their observations were within the expected daily variation and thus the calculated $\dot{V}O_{2max}$ corresponded with the measured value and was considered valid (Δ=0.13 mL·kg^{-1}·min^{-1}, p=0.885).

In the literature, several models have been developed to estimate $\dot{V}O_{2max}$ from practical performance tests or wearable technologies. Recently, the validity of $\dot{V}O_{2max}$ estimations from a wearable sportswatch has been investigated in 19 healthy individuals ($\dot{V}O_{2max}$ 48.9±6.7 mL min^{-1} kg^{-1}). The sportswatch assessed $\dot{V}O_{2max}$ in comparison with lab measurements from a metabolic cart with reasonable accuracy (Δ = 0.75 mL min^{-1} kg^{-1}; Δ95%CI: -1.3 to 2.8 mL min^{-1} kg^{-1}), although the sportswatch overestimated lower values (< 50 mL·min^{-1}·kg^{-1}) and underestimated higher values (> 50 mL·min^{-1}·kg^{-1}) [41]. Sitko et al investigated the utility of a 5-min maximal power test in trained cyclist ($\dot{V}O_{2max}$ 61.1±9.1 mL·min^{-1}·kg^{-1}) to estimate $\dot{V}O_{2max}$ and observed good correlations between the maximal 5-min power (W·kg^{-1}) with the measured $\dot{V}O_{2max}$ (r=0.84, p<0.001) [18]. A similar approach was used to assess $\dot{V}O_{2max}$ from a 3 min maximal test in trained subjects and revealed a good correlation (r=0.82, p<0.001) [42]. Noteworthy, the efforts used to predict $\dot{V}O_{2max}$ rely on both aerobic and glycolytic energy contribution [21]. However, these above-mentioned models do not include a measure of glycolytic energy production in the regression and as such assume a fixed glycolytic energy contribution in the tested efforts. In a cohort of subjects with homogeneous glycolytic capacities, such models may still provide accurate $\dot{V}O_{2max}$ assessments. However, the validity of these linear regression models in subjects with mixed glycolytic capacities is not yet documented in the literature. In the current study, we approached the $\dot{V}O_{2max}$ assessments with a mechanistic model for muscle metabolism. This model takes the individual glycolytic power ($\dot{V}$Lamax) into account. It can be speculated that this might have contributed to the high level of accuracy achieved in our study. Noteworthy, based on $\dot{V}O_{2max}$ and $\dot{V}$Lamax data, the metabolic profile of the athlete can be completed with information on the maximal lactate steady state [43] which can be used to define training recommendations, training zones or predict endurance performance [44].

Interestingly from a practical standpoint, our data demonstrate that accurate $\dot{V}O_{2max}$ estimations can be derived from cycling power alone. In recent years, the possibility of assessing the cycling power in the field has been made possible by the exponential rise in the use of power meters and smart trainers among professional and amateur cyclists. These user-friendly tools allow the collection of real-time and accurate power data in training and racing [45-47] and could reduce the need for formal exercise testing. It should ~~also~~ be noted that in this study a lab-grade ergometer was used. This ensured high quality input data to feed the mathematical model. This level of accuracy and measurement frequency is in general not met by consumer-based ergometers. Although some of these ergometers produce accurate data in the 200-400W range, they are less accurate to measure maximal sprinting power [48]. Our data demonstrated that despite some differences in sprinting power, we still obtained valid $\dot{V}O_{2max}$ calculations. We could speculate that consumer-based ergometers and power meters provide sufficiently accurate cycling power data to allow valid $\dot{V}O_{2max}$ assessments.

Some limitations in our study should be recognized. We acknowledge that our sample size was small (n=11) compared to the recommended sample size for this type of research (n=~30) [49]. Unfortunately, testing larger samples was not possible at the time of the data collection due to COVID restrictions for laboratory exercise testing. Secondly, no female subjects volunteered for this study, and this might limit the generalization of our findings to female athletes. Thirdly, in our sample VLamax values ranged between and ~0.3-0.65 $mmol \cdot l^{-1} \cdot s^{-1}$ typical for endurance trained athletes, whereas the range in an athletic population can vary between 0.2 and 1.2 $mmol \cdot l^{-1} \cdot s^{-1}$ [23]. Therefore, generalization of our findings to other populations with different VLamax values should be performed with some caution. Future research should focus on investigating the model on larger samples including female subjects.

5. Conclusions

Our findings demonstrate that $\dot{V}O_{2max}$ can be calculated accurately from three maximal cycling tests of 20" to 6' duration. This technology offers the opportunity to calculate a comprehensive metabolic profile from cycling power data. Such data can be acquired from training data or on the field testing, without the need for expensive laboratory equipment. Whether the model to calculate $\dot{V}O_{2max}$ will yield accurate results in females and in subjects with more extreme VLamax values needs further scientific investigation.

Abbreviations

BLX	Blood Lactate Concentration
CO_2	Carbon Dioxide
MET	Metabolic Equivalent of a Task
O_2	Oxygen
SPR1	Isokinetic Sprint n°1
SPR2	Isokinetic Sprint n°2
SPR3	Isokinetic Sprint n°3
TT_3	Three-minute All-out Time Trial
TT_6	Six-minute All-out Time Trial
VLamax	Maximal Glycolytic Rate
$\dot{V}O_{2max}$	Maximal Oxygen Consumption

Acknowledgments

The authors like to thank Jochem Wildershoven for his skillful assistance during the experimental trials and Prof. Sebastian Gehlert for his valuable comments on the manuscript.

Author Contributions

Reinout Van Schuylenbergh: Methodology, Formal analysis, Investigation, Methodology, Project administration, Resources, Project administration, Visualization, Writing – original draft, Writing – review & editing

Asatur Khurshudyan: Software, Writing – review & editing

Sebastian Weber: Conceptualization, Software, Methodology, Supervision, Writing – review & editing

Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Appendix

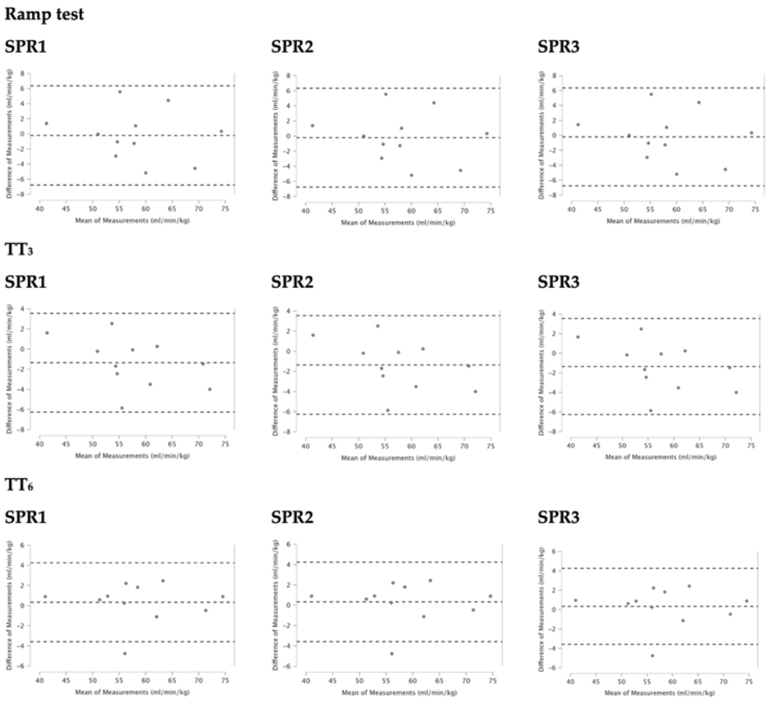

Figure 4. *Bland-Altman Analysis: Calculated* $\dot{V}O_{2max}$ *and the Measured* $\dot{V}O_{2max}$*, with ±1.96SD Range of Agreement (See Methods for More Details).*

References

[1] Cove, B.; Chalmers, S.; Nelson, M. J.; Anderson, M.; Bennett, H. The Effect of Training Distribution, Duration, and Volume on VO_{2max} and Performance in Trained Cyclists: A Systematic Review, Multilevel Meta-Analysis, and Multivariate Meta-Regression. *J. Sci. Med. Sport* 2025, *28*, 423–434, https://doi.org/10.1016/j.jsams.2024.12.005

[2] Coyle, E. Integration of the Physiological Factors Determining Endurance Performance Ability. *Exerc. Sport Sci. Rev.* 1995, *23*, 25–64.

[3] Støa, E. M.; Rønnestad, B.; Helgerud, J.; Johansen, J.-M.; Andersen, I. T.; Rognefløten, T.; Sørensen, A.; Støren, Ø. Short-Time Cycling Performance in Young Elite Cyclists: Related to Maximal Aerobic Power and Not to Maximal Accumulated Oxygen Deficit. *Front. Physiol.* 2025, *15*, 1536874, https://doi.org/10.3389/fphys.2024.1536874

[4] Pedersen, B. K.; Saltin, B. Exercise as Medicine – Evidence for Prescribing Exercise as Therapy in 26 Different Chronic Diseases. *Scand. J. Med. Sci. Sports* 2015, *25*, 1–72, https://doi.org/10.1111/sms.12581

[5] Ross, R.; Blair, S. N.; Arena, R.; Church, T. S.; Després, J.-P.; Franklin, B. A.; Haskell, W. L.; Kaminsky, L. A.; Levine, B. D.; Lavie, C. J.; et al. Importance of Assessing Cardiorespiratory Fitness in Clinical Practice: A Case for Fitness as a Clinical Vital Sign: A Scientific Statement From the American Heart Association. *Circulation* 2016, *134*, https://doi.org/10.1161/CIR.0000000000000461

[6] Strasser, B.; Burtscher, M. Survival of the Fittest: VO_{2max}, a Key Predictor of Longevity? *Front. Biosci. Landmark Ed.* 2018, *23*, 1505–1516, https://doi.org/10.2741/4657

[7] Haugen, T.; Paulsen, G.; Seiler, S.; Sandbakk, Ø. New Records in Human Power. *Int. J. Sports Physiol. Perform.* 2018, *13*, 678–686, https://doi.org/10.1123/ijspp.2017-0441

[8] Rønnestad, B. R.; Hansen, J.; Stensløkken, L.; Joyner, M. J.; Lundby, C. Case Studies in Physiology: Temporal Changes in Determinants of Aerobic Performance in Individual Going from Alpine Skier to World Junior Champion Time Trial Cyclist. *J. Appl. Physiol.* 2019, *127*, 306–311, https://doi.org/10.1152/japplphysiol.00798.2018

[9] Loe, H.; Rognmo, Ø.; Saltin, B.; Wisløff, U. Aerobic Capacity Reference Data in 3816 Healthy Men and Women 20–90 Years. *PLoS ONE* 2013, *8*, e64319, https://doi.org/10.1371/journal.pone.0064319

[10] Valenzuela, P. L.; Maffiuletti, N. A.; Joyner, M. J.; Lucia, A.; Lepers, R. Lifelong Endurance Exercise as a Countermeasure Against Age-Related VO_{2max} Decline: Physiological Overview and Insights from Masters Athletes. *Sports Med.* 2020, *50*, 703–716, https://doi.org/10.1007/s40279-019-01252-0

[11] Skinner, J. S.; Jaskólski, A.; Jaskólska, A.; Krasnoff, J.; Gagnon, J.; Leon, A. S.; Rao, D. C.; Wilmore, J. H.; Bouchard, C. Age, Sex, Race, Initial Fitness, and Response to Training: The HERITAGE Family Study. *J. Appl. Physiol.* 2001, *90*, 1770–1776, https://doi.org/10.1152/jappl.2001.90.5.1770

[12] Odden, I.; Nymoen, L.; Urianstad, T.; Kristoffersen, M.; Hammarström, D.; Hansen, J.; Mølmen, K. S.; Rønnestad, B. R. The Higher the Fraction of Maximal Oxygen Uptake Is during Interval Training, the Greater Is the Cycling Performance Gain. *Eur. J. Sport Sci.* 2024, ejsc. 12202, https://doi.org/10.1002/ejsc.12202

[13] Foster, C.; Green, M.; Snyder, A.; Thomson, N. Physiological Responses during Simulated Competition. *Med. Sci. Sports Exerc.* 1993, *25*, 877–882. https://doi.org/10.1249/00005768-199307000-00018

[14] Liguori, G.; Feito, Y.; Fountaine, C.; Roy, B.; American College of Sports Medicine other *ACSM's Guidelines for Exercise Testing and Prescription*; American College of Sports Medicine's guidelines for exercise testing and prescription; Eleventh edition.; Wolters Kluwer: Philadelphia, 2022.

[15] Midgley, A. W.; Bentley, D. J.; Luttikholt, H.; McNaughton, L. R.; Millet, G. P. Challenging a Dogma of Exercise Physiology: Does an Incremental Exercise Test for Valid VO_{2max} Determination Really Need to Last Between 8 and 12 Minutes? *Sports Med.* 2008, *38*, 441–447, https://doi.org/10.2165/00007256-200838060-00001

[16] Beltz, N. M.; Gibson, A. L.; Janot, J. M.; Kravitz, L.; Mermier, C. M.; Dalleck, L. C. Graded Exercise Testing Protocols for the Determination of VO_2 Max: Historical Perspectives, Progress, and Future Considerations. *J. Sports Med.* 2016, *2016*, 1–12, https://doi.org/10.1155/2016/3968393

[17] Van Hooren, B.; Souren, T.; Bongers, B. C. Accuracy of Respiratory Gas Variables, Substrate, and Energy Use from 15 CPET Systems during Simulated and Human Exercise. *Scand. J. Med. Sci. Sports* 2023, sms. 14490, https://doi.org/10.1111/sms.14490

[18] Sitko, S.; Cirer-Sastre, R.; Corbi, F.; López-Laval, I. Five-Minute Power-Based Test to Predict Maximal Oxygen Consumption in Road Cycling. *Int. J. Sports Physiol. Perform.* 2022, *17*, 9–15, https://doi.org/10.1123/ijspp.2020-0923

[19] Seiler, S.; Jøranson, K.; Olesen, B. V.; Hetlelid, K. J. Adaptations to Aerobic Interval Training: Interactive Effects of Exercise Intensity and Total Work Duration. *Scand. J. Med. Sci. Sports* 2013, *23*, 74–83, https://doi.org/10.1111/j.1600-0838.2011.01351.x

[20] Matzka, M.; Lenk, M.; Meixner, B.; Sperlich, B. Meta-analysis of High-intensity Interval Training and Alternative Modalities for Enhancing Aerobic and Anaerobic Endurance in Young Athletes. *Physiol. Rep.* 2025, *13*, e70598, https://doi.org/10.14814/phy2.70598

[21] Gastin, P. B. Energy System Interaction and Relative Contribution During Maximal Exercise: *Sports Med.* 2001, *31*, 725–741, https://doi.org/10.2165/00007256-200131100-00003

[22] Clark, B.; Macdermid, P. W. VLa_{max} Correlates Strongly With Glycolytic Performance. *Res. Q. Exerc. Sport* 2025, 1–8, https://doi.org/10.1080/02701367.2025.2481176

[23] Quittmann, O. J. Maximal Lactate Accumulation Rate cLamax: Current Evidence and Future Directions for Exercise Testing and Training. *Eur. J. Appl. Physiol.* 2025, https://doi.org/10.1007/s00421-025-06022-7

[24] Mader, A. Eine Theorie zur Berechnung der Dynamik und des steady state von Phosphorylierungszustand und Stoffwechselaktivitaet der Muskelzelle als Folge des Energiebedarfs [A theory for calculating the dynamics and steady state of the phosphorylation state and metabolic activity of the muscle cell as a consequence of energy demand]; Deutsche Sporthochschule Köln: Köln, 1984.

[25] Mader, A. Glycolysis and Oxidative Phosphorylation as a Function of Cytosolic Phosphorylation State and Power Output of the Muscle Cell. *Eur. J. Appl. Physiol.* 2003, *88*, 317–338, https://doi.org/10.1007/s00421-002-0676-3

[26] Mader, A.; Heck, H. A Theory of the Metabolic Origin of "Anaerobic Threshold." *Int J Sports Med* 1986, *7*, 45–65.

[27] Mader, A. Anaerobic Threshold (AT) as Determined by VO_{2max} and Vlamax of the Working Muscle Mass of the Human Body - an Update of the Theoretical Concept.; European College of Sport Science: Rome, July 17 1999; p. 14.

[28] Dunst, A. K.; Hesse, C.; Ueberschär, O.; Holmberg, H.-C. Fatigue-Free Force-Velocity and Power-Velocity Profiles for Elite Track Sprint Cyclists: The Influence of Duration, Gear Ratio and Pedalling Rates. *Sports* 2022, *10*, 130, https://doi.org/10.3390/sports10090130

[29] Dunst, A. K.; Hesse, C.; Ueberschär, O. Enhancing Endurance Performance Predictions: The Role of Movement Velocity in Metabolic Simulations Demonstrated by Cycling Cadence. *Eur. J. Appl. Physiol.* 2025, https://doi.org/10.1007/s00421-024-05663-4

[30] Heck, H.; Schulz, H.; Bartmus, U. Diagnostics of Anaerobic Power and Capacity. *Eur. J. Sport Sci.* 2003, *3*, 1–23, https://doi.org/10.1080/17461390300073302

[31] Pohl, A.; Schünemann, F.; Schaaf, K.; Yang, W.; Heck, H.; Heine, O.; Jacko, D.; Gehlert, S. Increased Resting Lactate Levels and Reduced Carbohydrate Intake Cause vLa. Max Underestimation by Reducing Net Lactate Accumulation—A Pilot Study in Young Adults. *Physiol. Rep.* 2024, *12*, e70020, https://doi.org/10.14814/phy2.70020

[32] Van Schuylenbergh, R.; Vanden Eynde, B.; Hespel, P. Effects of Air Ventilation during Stationary Exercise Testing. *Eur. J. Appl. Physiol.* 2004, *92*, 263–266, https://doi.org/10.1007/s00421-004-1087-4

[33] Schoffelen, P. F. M.; Den Hoed, M.; Van Breda, E.; Plasqui, G. Test-retest Variability of VO2max Using Total-capture Indirect Calorimetry Reveals Linear Relationship of VO_2 and Power. *Scand. J. Med. Sci. Sports* 2019, *29*, 213–222, https://doi.org/10.1111/sms.13324

[34] Martin-Rincon, M.; Calbet, J. A. L. Progress Update and Challenges on $V.O_{2max}$ Testing and Interpretation. *Front. Physiol.* 2020, *11*, 1070, https://doi.org/10.3389/fphys.2020.01070

[35] Balady, G. J.; Arena, R.; Sietsema, K.; Myers, J.; Coke, L.; Fletcher, G. F.; Forman, D.; Franklin, B.; Guazzi, M.; Gulati, M.; et al. Clinician's Guide to Cardiopulmonary Exercise Testing in Adults: A Scientific Statement From the American Heart Association. *Circulation* 2010, *122*, 191–225, https://doi.org/10.1161/CIR.0b013e3181e52e69

[36] Wackerhage, H.; Gehlert, S.; Schulz, H.; Weber, S.; Ring-Dimitriou, S.; Heine, O. Lactate Thresholds and the Simulation of Human Energy Metabolism: Contributions by the Cologne Sports Medicine Group in the 1970s and 1980s. *Front. Physiol.* 2022, *13*, 899670, https://doi.org/10.3389/fphys.2022.899670

[37] Wackerhage, H. Contributions by the Cologne Group to the Development of Lactate Exercise Testing and Anaerobic Threshold Concepts in the 1970s and 1980s. *J. Physiol.* 2021, *599*, 1713–1714, https://doi.org/10.1113/JP281142

[38] Koo, T. K.; Li, M. Y. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J. Chiropr. Med.* 2016, *15*, 155–163, https://doi.org/10.1016/j.jcm.2016.02.012

[39] Knaier, R.; Infanger, D.; Niemeyer, M.; Cajochen, C.; Schmidt-Trucksäss, A. In Athletes, the Diurnal Variations in Maximum Oxygen Uptake Are More Than Twice as Large as the Day-to-Day Variations. *Front. Physiol.* 2019, *10*, 219, https://doi.org/10.3389/fphys.2019.00219

[40] Podlogar, T.; Cirnski, S.; Bokal, Š.; Kogoj, T. Utility of INSCYD Athletic Performance Software to Determine Maximal Lactate Steady State and Maximal Oxygen Uptake in Cyclists. *J. Sci. Cycl.* 2022, *11*, 30–38, https://doi.org/10.28985/1322.jsc.06

[41] Carrier, B.; Marten Chaves, S.; Navalta, J. W. Validation of Aerobic Capacity (VO_{2max}) and Pulse Oximetry in Wearable Technology. *Sensors* 2025, *25*, 275, https://doi.org/10.3390/s25010275

[42] Dexheimer, J. D.; Brinson, S. J.; Pettitt, R. W.; Schroeder, E. T.; Sawyer, B. J.; Jo, E. Predicting Maximal Oxygen Uptake Using the 3-Minute All-Out Test in High-Intensity Functional Training Athletes. *Sports* 2020, *8*, 155, https://doi.org/10.3390/sports8120155

[43] Poffé, C.; Van Dael, K.; Van Schuylenbergh, R. INSCYD Physiological Performance Software Is Valid to Determine the Maximal Lactate Steady State in Male and Female Cyclists. *Front. Sports Act. Living* 2024, *6*, 1376876, https://doi.org/10.3389/fspor.2024.1376876

[44] Billat, V. L.; Sirvent, P.; Py, G.; Koralsztein, J.-P.; Mercier, J. The Concept of Maximal Lactate Steady State: A Bridge Between Biochemistry, Physiology and Sport Science. *Sports Med.* 2003, *33*, 407–426, https://doi.org/10.2165/00007256-200333060-00003

[45] Passfield, L.; Hopker, Jg.; Jobson, S.; Friel, D.; Zabala, M. Knowledge Is Power: Issues of Measuring Training and Performance in Cycling. *J. Sports Sci.* 2017, *35*, 1426–1434, https://doi.org/10.1080/02640414.2016.1215504

[46] Spragg, J.; Leo, P. Can Critical Power Be Estimated from Training and Racing Data Using Mean Maximal Power Outputs? 2020. *J Sci Cycl* 9(2): 7-10.

[47] Gonzalez, J. T.; Helleputte, S.; Van Erp, T.; Green, D.; Podlogar, T.; Derave, W.; Jeukendrup, A.; Burke, L. M. Nutritionally Relevant Technological Advancements in Professional Cycling. *Int. J. Sport Nutr. Exerc. Metab.* 2025, 1–13, https://doi.org/10.1123/ijsnem.2025-0048

[48] Zadow, E. K.; Kitic, C. M.; Wu, S. S. X.; Smith, S. T.; Fell, J. W. Validity of Power Settings of the Wahoo KICKR Power Trainer. *Int. J. Sports Physiol. Perform.* 2016, *11*, 1115–1117, https://doi.org/10.1123/ijspp.2015-0733

[49] Mondal, D.; Vanbelle, S.; Cassese, A.; Candel, M. J. Review of Sample Size Determination Methods for the Intraclass Correlation Coefficient in the One-Way Analysis of Variance Model. *Stat. Methods Med. Res.* 2024, *33*, 532–553, https://doi.org/10.1177/09622802231224657

Biography

Reinout Van Schuylenbergh is research manager at INSCYD GmbH. He completed his PhD in Exercise physiology and biomechanics from Leuven University in 2006, and his Master of Physical education from the same institution in 1995. He authored and co-authored peer-reviewed scientific manuscripts in applied exercise physiology.

Asatur Khurshudyan is a mathematician at INSCYD GmbH. He obtained his PhD degree in Mechanics from the Institute of Mechanics, NAS of Armenia in 2016. He authored and co-authored over 35 peer-reviewed scientific manuscripts in applied mathematics field including one award-winning monograph.

Sebastian Weber is project leader of INSCYD. He obtained his Ms degree in Sport Science with distinction at German Sport University Cologne, Germany in 2003 and has been a coach in professional cycling and advisor in elite triathlon and swimming since 2006.

Research Field

Reinout Van Schuylenbergh: Exercise physiology, Cycling, triathlon, elite-training, endurance training.

Asatur Khurshudyan: Mathematics, mathematical modelling, software development.

Sebastian Weber: Exercise physiology, Cycling, triathlon, elite-training, endurance training, software development.