Training & Testing

Comparison of Modelled Maximal Lactate Steady State with Critical Power in Elite Cyclists

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ABSTRACT

The aim of the current study was to compare modelled maximal lactate steady state with the field-based assessment of critical power in a group of highly trained pro cyclists. As a secondary objective, the relationships of the maximal rate of blood lactate accumulation and maximal oxygen consumption with outdoor maximal mean power output of different durations were explored. Twelve highly trained male professional cyclists performed six successive maximal tests. The maximal lactate steady state was calculated using the maximal rate of blood lactate accumulation, maximal oxygen consumption, resting oxygen uptake and body mass as input parameters. The critical power was estimated using the 3-minute and 20-minute maximal mean power outputs. The mean of the modelled maximal lactate steady state was 357 ± 30.6 W, while the mean of critical power was 364 ± 21.5 W; the modelled maximal lactate steady state and critical power correlated significantly ($r = 0.881$ and $p < 0.001$). The maximal oxygen consumption correlated with the 3-minute maximal mean power ($r = 0.646$ and $p = 0.023$), 20-minute maximal mean power ($r = 0.846$ and $p < 0.001$) and critical power ($r = 0.858$ and $p < 0.001$). No significant correlations were found between maximal rate of blood lactate accumulation and any of the outdoor maximal mean power outputs. The modelled maximal lactate steady state seems to predict critical power well on a group level; however, a substantial individual variation in the difference between the modelled maximal lactate steady state and critical power was observed. This individual variation would argue against conceptual similarity between the critical power and maximal lactate steady state model, which practitioners working within cycling should be aware of.

Keywords blood lactate, maximal oxygen consumption, maximal lactate accumulation rate, power output, physiological assessment

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Introduction

Competitive road cycling is an endurance sport encompassing both mass-start and individual time trial events. A professional cyclist typically competes in a variation of both multiday races and one-day races.[1] Due to the variation in race profiles, terrains and tactics, there is a wide variation in characteristics to successfully compete in those different race types which lead to the specialization of riders to those race types that fit best their capabilities (e.g., sprinter vs. climber).[2,3]

To appropriately apply a training stimulus to a high-level cyclist, an assessment of their physiological and functional capacity is typically applied in both field and laboratory settings. This includes assessing a rider's 'power profile', i.e., the maximal mean power output (MMP) they can produce over a variety of durations (e.g., typically ranging from 5 s to 60 min). In addition to this, MMP field data can be used to estimate an individual's sustainable power output, critical power (CP).[4] Furthermore, physiological (laboratory-based) assessments are conducted to complement the functional power output data collected in the field. Conventionally, maximal aerobic power is measured during a graded exercise test to exhaustion on a stationary bike with simultaneous measurements of oxygen consumption (maximal oxygen consumption or $\dot{V}O_{2max}$), which is commonly seen as the upper limit of aerobic physiology.[5] While $\dot{V}O_{2max}$ correlates significantly with power output during the outdoor time trial of durations from 8 to 20 minutes,[6–8] athletes with similar $\dot{V}O_{2max}$ still range substantially in endurance performance.[9] Notably, endurance performance is better represented by the fraction of $\dot{V}O_{2max}$ that can be sustained over time, which is, among others, related to the lactate production rate and muscle capillary density.[9] This intensity is described as the highest workload at which lactate production equals lactate elimination and therefore does not lead to net lactate accumulation and a steady state of lactate concentration can be reached,[10,11] which is referred to as the maximal lactate steady state (MLSS). Power at the MLSS is a significant predictor of performance in endurance activities of 30 to 60 minutes.[12] Thus, the use of a threshold concept, like MLSS, to predict endurance performance appears superior to $\dot{V}O_{2max}$. The gold standard method to determine one's MLSS is to perform several constant load tests of 30 minutes. The MLSS is the highest workload that can be maintained for 30 minutes without an increase of blood lactate concentration of more than 1 mmol/L during the last 20 minutes of the test.[12] For the valid assessment of MLSS, multiple constant load tests of 30 minutes each are required and sufficient rest between tests are needed. Thus, using the golden standard method to assess MLSS is logistically challenging and the application in sports practice is limited for elite athletes with busy training and competition schedules.

Based on mathematical modelling and simulations of lactate production and oxidation rates of a single muscle cell published by Mader and Heck,[13] a model has been developed to calculate one's power at the MLSS based on different input parameters. The input parameters to model the MLSS consists of resting oxygen consumption, maximal oxygen consumption and the maximal rate of lactate accumulation per litre of blood ($\dot{V}La_{max}$).[14] In recreational endurance athletes ($\dot{V}O_{2max}$: 60.4 mL/min/kg), modelled and measured MLSS correlated tightly ($r = 0.92$ and $p < 0.001$).[14] Nevertheless, the individual variation in the difference between the modelled and measured MLSS was substantial in this group with a heterogeneous training status. Therefore, its applicability in a population of highly trained cyclists remains questionable.[15–18]

Alternatively, a common easy-to-implement tool for determining performance and set training intensities is CP. CP is seen as the maximal capacity of a muscle or muscle group to perform work for a prolonged amount of time and can be tested by a minimum of two maximal tests between the durations of 3 to 20 minutes. Cycling below CP can theoretically be sustained for almost an infinite time and cycling above CP has a finite capacity which is referred to as W prime (W′).[4] The concepts behind MLSS and CP could be argued to be the same, a threshold which divides sustainable from non-stainable exercise intensities. In previous research, power at MLSS and CP have already been shown to correlate significantly but was still highly variable in absolute terms.[15–18] As the use of CP in practice is very common, the relationship of it with the golden standard endurance markers is practically important; however, this relationship remains understudied in highly trained cyclists.

As race decisive moments are often short burst of high intensity efforts, which are not reflected in the classical endurance markers, interest has grown in the assessment of anaerobic energy production capacity. While W' was believed to be an anaerobic energy store, this has been questioned by findings that it relates to the kinetics of the $\dot{V}O_2$ response, which suggest that it might not be a true reflection of underlying physiological capacity to produce power anaerobically.[19] While $\dot{V}La_{max}$ should reflect the maximal lactate formation rate ($\dot{V}La_{max}$), which is an estimation of the maximum amount of energy per second that can be produced anaerobically by a subject.[20] Additionally, it is theorized that a higher $\dot{V}La_{max}$ leads to a higher lactate concentration at the same workload and a reduced MLSS,[21] and therefore influencing the sustainable workload without changes in maximal oxygen consumption.

For these reasons, combining the assessment of the laboratory-based parameters with practically used measures in field (like CP) could improve rider allocation to race types and can be used as a useful tool for the precise and individual monitoring of training adaptations and performance progression.

Most studies on the application of modelled MLSS and CP measurements to profile riders have, however, been performed in trained amateur or recreational riders.[14, 22, 23] It is unknown if these results can be validly extrapolated to elite pro cyclists.

Thus, this study aimed to compare the modelled MLSS with the field-based assessment of CP in a group of highly trained male pro cyclists. As a secondary objective, the relationships of $\dot{V}La_{max}$ and $\dot{V}O_{2max}$ with outdoor maximal mean power outputs of different durations were explored.

Methods

Subjects

The study population consisted of 12 highly trained male pro cyclists with an average annual training volume of 759 ± 97 hours in the season preceding the testing (October 2019 to September 2020) and all were a member of a Union Cycliste Internationale continental team competing in international races. The participants of the current study can be classified as performance level 5 according to the classification by de Pauw et al.,[24] and tier 3 to tier 4 according to the classification of McKay et al.[25] The mean age of the participants was 18.9 ± 1.0 years, the mean height was 181.0 ± 4.7 cm, and the mean body mass was 67.9 ± 4.7 kg. All individuals presented in this paper were hired by a professional cycling team. Data shown were obtained as part of their daily team-induced training regimes. In line with their team contract, the riders approved publishing these anonymized data. The institutional review board approved this procedure. This study was executed in agreement with the principles of the declaration of Helsinki.

Study design

In a cross-sectional design, the participants performed six maximal tests: two indoor laboratory tests on a stationary bike and four outdoor field tests. During the indoor laboratory tests, the input data for the modelled MLSS (body mass, resting $\dot{V}O_2$, $\dot{V}O_{2max}$, and $\dot{V}La_{max}$) were acquired. With the reason to obtain $\dot{V}La_{max}$ and $\dot{V}O_{2max}$, riders' personalized team bike equipped with a power meter (Shimano Dura-Ace R9100 Power Meter, Sakai, Japan) was connected to an ergometer to control the resistance (Elite Drivo II, Fontaniva, Italy).

In the field, two time-trial tests of 3 and 20 minutes were used to assess CP, along with a 10-second and 1-minute time–trial test for a more complete profile of outdoor maximal power outputs over a range of durations.

Participant's $\dot{V}O_{2max}$ and $\dot{V}La_{max}$ were measured within a time span of 6 days. The 3-minute and 20-minute maximal tests were executed on the same or on 2 consecutive days. The 10-second and 1-minute maximal tests were executed on the same day. All required tests were done within a period of 34 days. To minimise the influence of exercise-induced fatigue on test performance, participants refrained from high-intensity exercise in the 48 hours preceding each maximal test.

The maximal rate of blood lactate accumulation test

Methodologies based on previously described protocols to estimate an individual's maximal lactate accumulation rate ($\dot{V}La_{max}$) were applied, aligning with the protocol used for the calculation of modelled MLSS.[14,23]

The $\dot{V}La_{max}$ test started with a warm-up of 5 minutes at 50 % of participant's current CP and then a 5 second standing warm-up sprint followed by a 4-minute recovery period at 50 % of CP. At the end of this period, a baseline blood lactate measurement was taken.

After the recovery period, the sprint test was performed, during which the participants were instructed to deliver an all-out standing sprint for 15 seconds. For the sprints, the resistance of the Elite Drivo II turbo trainer was set at maximum at the onset of the sprint to allow sufficient resistance at the initial peak power phase. After 15 seconds, the participants stopped pedalling, whilst remaining on the bike. Blood samples were taken from the ear lobe and were immediately analysed for blood lactate concentration using the lactate oxidase enzyme electrode method (Lactate Pro 2, Arkray Global Business INC, Kyoto, Japan). The post-sprint test blood lactate concentration was measured every 60 seconds starting 1.5 minutes after the end of the sprint test, until the peak blood lactate value was reached (The last measured value decreased with respect to the one before).

The $\dot{V}La_{max}$ was calculated using equation 1:

$$VLa_{\ max} = \frac{La_{\max Post} - La_{Pre}}{T_{Test} - T_{alac}}$$

Equation 1: Calculation of the $\dot{V}La_{max}$. $La_{max\,post}$ is the highest measured post-sprint blood lactate concentration. La_{pre} is the pre-sprint or baseline blood lactate concentration. T_{Test} is the time of the sprint, which was 15 seconds. T_{alac} is the alactic time interval, the time for which no lactate production can be assumed, which was defined as the time until the power output decreased by more as 3.5 % compared to the maximal power output.[20]

It needs to be acknowledged that the $\dot{V}La_{max}$ can merely be an estimation of the muscular lactate production rate, given that the concentration of lactate in the blood is a balance between the rate of production and utilisation of different tissues, rather than the production of the active muscle mass alone.

Maximal oxygen consumption test

Maximal oxygen consumption ($\dot{V}O_{2max}$) was assessed using a ramp test with the breath-by-breath measurement of oxygen uptake using a metabolic cart (Quark RMR, COSMED, Italy). The metabolic cart was calibrated according to the manufacturer's instructions before each measurement, including gas calibration against a known gas mixture and volume calibration using a 3 L syringe. After a 10-minute warm up, the ramp protocol started at 150 W and increased with 30 W steps each minute until the participant reached voluntary exhaustion. The $\dot{V}O_{2max}$ was defined as the highest mean of all measured $\dot{V}O_2$ values over a period of 30 seconds.

Body composition and resting oxygen uptake measurements

Resting oxygen uptake ($\dot{V}O_{2rest}$) was measured in the morning, just after waking up but before breakfast using a metabolic cart (Quark RMR, COSMED, Italy). The measurement started while laying down and as soon as stable $\dot{V}O_2$ values were recorded (~10 min). The lowest mean oxygen uptake averaged over 5 minutes was defined as $\dot{V}O_{2rest}$. Due to logistical reasons for two participants, the resting oxygen uptake was estimated based on height, age and body mass using the Harris–Benedict equation.[26] Body mass was measured in the morning before the $\dot{V}O_{2max}$ test using a body analysis scale (BS430, Medisana GmbH, Neuss, Germany).

Modelling of the maximal lactate steady state

The mathematical models underlying the calculation of the modelled MLSS have been extensively described elsewhere.[13] The relevant equations and modelling approach to calculate the MLSS have been described previously by Hauser et al.[14] Hence, for the exact equations used, we refer to the previously published papers and refrain from describing them in detail here.[13,14] Input parameters for the modelled MLSS were the measured $\dot{V}La_{max}$, $\dot{V}O_{2max}$, $\dot{V}O_{2rest}$ and body mass. The model was build using Matlab version R2020b (MathWorks Inc, Natick, United States). The $\dot{V}La_{ss}$ and $\dot{V}La_{oxmax}$ were programmed in separate functions and their intersection was computed using a vectorization method and corresponds with modelled MLSS.

Field tests and critical power assessments

The mean maximal power output (MMP) of participants was tested for the durations of 20-, 3-, 1-minute and 10 seconds in field. These tests were performed on the participant's own bike equipped with a calibrated power meter. All tests were executed after a warm-up of at least 30 minutes. The maximal tests of 10 seconds and 1-minute were performed on the very same day, interspaced by at least 30 minutes of rest. Depending on logistics and training schedules, the field tests of 3- and 20- minutes were either performed on 1 day or on 2 consecutive days. For logistic reasons, three participants performed their field tests of 3- and 20-minutes on the same day and separated by an active recovery period of at least 30 minutes. The remaining 10 participants performed the 3- and 20- minutes tests on 2 consecutive days, in the same order (the 3-minute maximal test on day 1 and the 20-minute test on day 2).

The CP was calculated using the mean maximal power output of the 3- and 20-minute field tests. For each duration, the number of kilojoules spent was calculated and plotted against the duration of the test. A linear regression model was fitted through both points, of which the slope represented the CP and the y-intercept represented the W'.[4]

Statistical analysis

Statistical analysis was performed using GraphPad Prism (version 8.4.3; GraphPad Software, San Diego, USA). Descriptive values are reported as mean ± standard deviation. The association between the modelled MLSS and CP was tested using Pearson's correlation, and the difference was tested using a paired sample *t*-test. In addition, bias between modelled MLSS and CP was assessed using a Bland–Altman plot. The associations between the laboratory and field measurements were analysed using linear regression and Pearson's correlation. A *p*-value of less than 0.05 was assumed to be statistically significant.

Results

Comparison of the modelled MLSS with CP

In total, 12 participants were included in the study, who all performed the $\dot{V}O_{2max}$, $\dot{V}La_{max}$, 10 second, 1-minute, 3-minute and 20-minute tests. The results of the measurements of each participant for body mass, $\dot{V}La_{max}$, $\dot{V}O_{2max}$, $\dot{V}O_{2rest}$, CP and modelled MLSS are presented in **Table 1**, including the difference between the CP and the modelled MLSS.

The CP correlated positively and significantly with modelled MLSS ($r = 0.881$, $p < 0.001$, **Fig. 1**) and there was no significant difference ($p = 0.146$ and confidence interval: − 16.66 to 2.823). The difference of the mean of CP and modelled MLSS was 6.9 ± 15.3 W. The 95 % limits of agreement between the modelled MLSS and CP were equal to − 23.1 to 37.0 W, as shown in the Bland–Altman plot, see **Fig. 2**.

Thus, modelled MLSS showed a strong linear relationship with CP, but there is quite a large variation of bias between modelled MLSS and CP in individual values in this group of highly trained cyclists.

Relationship between laboratory measurements and field test data

The relationship between the laboratory and field measurements have been analysed using Pearson's linear regression analysis. In **Fig. 3**, the linear regression analyses are shown between $\dot{V}O_{2max}$ and the maximal mean power outputs of different durations as tested in the field, including CP and W′. The same field-based performance measures and their linear regression analysis against $\dot{V}La_{max}$ are shown in **Fig. 4**.

Significant linear correlations were found between laboratory based $\dot{V}O_{2max}$ and the field based MMP 3-minute ($r = 0.646$ and $p = 0.023$), MMP 20-minute ($r = 0.846$ and $p < 0.001$) and CP ($r = 0.858$ and $p < 0.001$). $\dot{V}La_{max}$ did not correlate significantly with any of the field measurements nor CP ($r = -0.155$ and $p = 0.631$) or W′ ($r = 0.413$ and $p = 0.182$). Thus, $\dot{V}O_{2max}$ correlated best with exercise of longer durations relying on a strong aerobic component. At shorter durations, during which there is relatively high contribution from glycolytic pathways for energy production, no significant correlation with $\dot{V}La_{max}$ was detected.

Table 1 Results of measurements and the calculation of CP and modelled MLSS of each participant

Participant	Body mass (kg)	$\dot{V}La_{max}$ (mmol/L/min)	$\dot{V}O_{2max}$ (mL/min/kg)	$\dot{V}O_{2rest}$ (mL/min/kg)	Modelled MLSS (W)	CP (W)	Difference[a]
1	63.8	1.010	81.9	3.82[b]	341	354	13
2	73.6	0.631	81.7	5.18	410	396	− 14
3	62.7	0.425	77.5	5.49	341	338	− 3
4	65.9	0.357	84.3	4.75	406	394	− 12
5	73.5	0.614	75.8	5.26	375	383	8
6	66.8	0.792	75.4	5.34	327	342	15
7	69.0	0.669	77.9	5.36	360	354	− 6
8	76.8	0.650	74.7	4.70	386	385	− 1
9	65.4	0.813	75.3	4.70	322	341	19
10	69.8	0.967	76.8	4.77	342	379	37
11	65.8	0.709	78.6	3.76[b]	353	356	3
12	62.0	0.408	73.5	3.77	327	351	24
Mean	67.9	0.670	77.78	4.74	357	364	6.9
Standard deviation	4.69	0.207	3.31	0.64	30.6	21.5	15.3

Abbreviations: CP, critical power; MLSS, maximal lactate steady state; $\dot{V}La_{max}$, maximal rate of blood lactate accumulation; $\dot{V}O_{2max}$, maximal oxygen consumption; $\dot{V}O_{2rest}$, resting oxygen uptake.

[a]Difference is the CP minus modelled MLSS.

[b]The VO_{2rest} has not been measured. The reported result is the estimated VO_{2rest} by the Harris–Benedict equations as reported before. This value has also been used for the calculation of modelled MLSS.

Discussion

The principal aim of the current study was to compare modelled MLSS with CP determined by maximal trials in field in a group of highly trained male pro cyclists. CP did not differ significantly from modelled MLSS and correlated significantly with modelled MLSS ($r = 0.881$ and $p < 0.001$). The mean difference between CP and modelled MLSS was 6.9 ± 15.3 W (i.e., 364 W vs. 357 W). Nevertheless, a substantial individual variation in the agreement between CP and modelled MLSS was observed ranging from − 14 to 37 W. Therefore, physiological equivalence or interchangeability on the individual level of modelled MLSS and CP cannot be concluded out of the current study.

In previous research, experimentally measured MLSS was compared against modelled MLSS using laboratory test data[14] and revealed a difference between modelled MLSS and measured MLSS of 12 ± 20 W, with modelled MLSS being modestly higher as measured MLSS.[14] This research provided some first insight into the validity of the Mader and Heck model in modelling sustainable power output in cyclists. However, in practice, MLSS is not as extensively

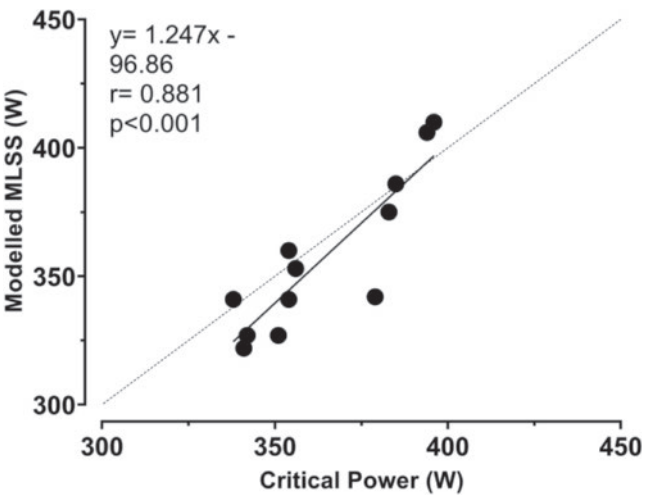

Fig. 1 Linear regression of the modelled MLSS with CP. Dotted line: line of identity ($y = x$). Solid line: line of best fit ($y = 1.247 \times - 96.86$).

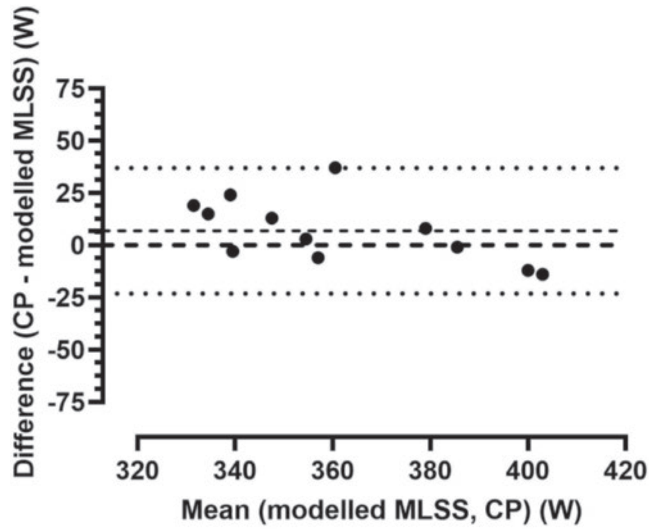

Fig. 2 The Bland–Altman plot of the difference between modelled MLSS and the critical power (CP). The 95 % limits of agreement are plotted with a dotted line. Bias is plotted with a thin interspaced line.

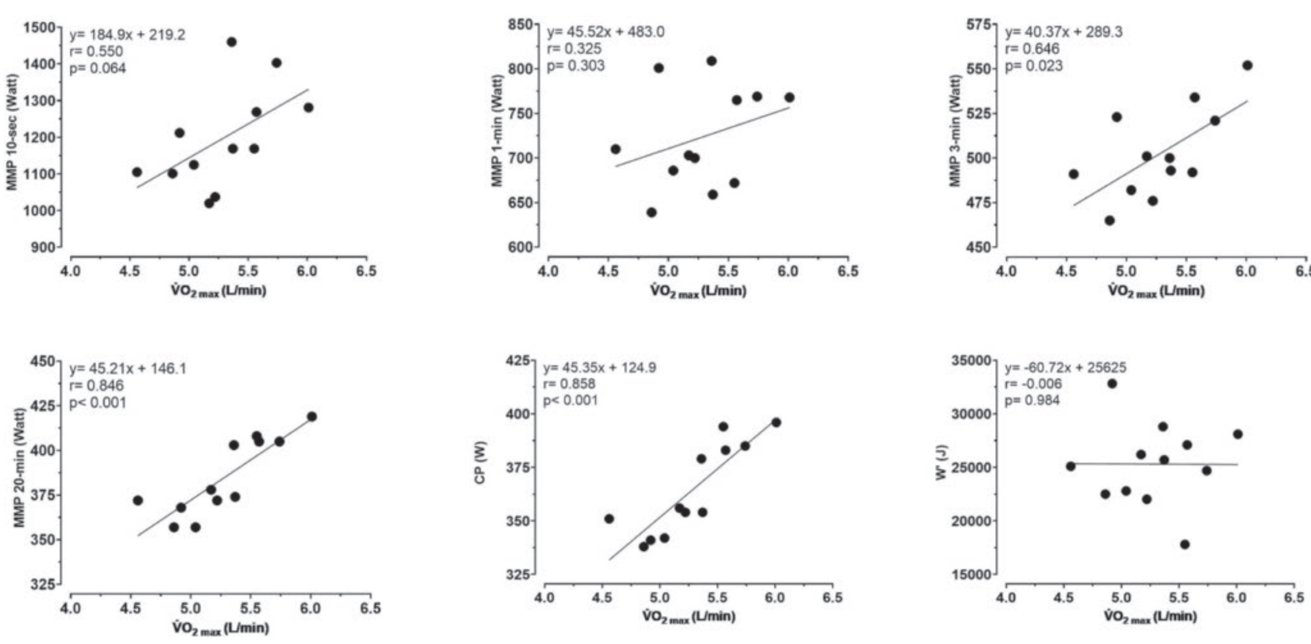

Fig. 3 Linear regression analysis of $\dot{V}O_{2max}$ and outdoor tested mean maximal power output of different durations (MMP10-second, MMP 1-minute, MMP 3-minute, and MMP 20-minute) and calculated threshold parameters (CP and W′).

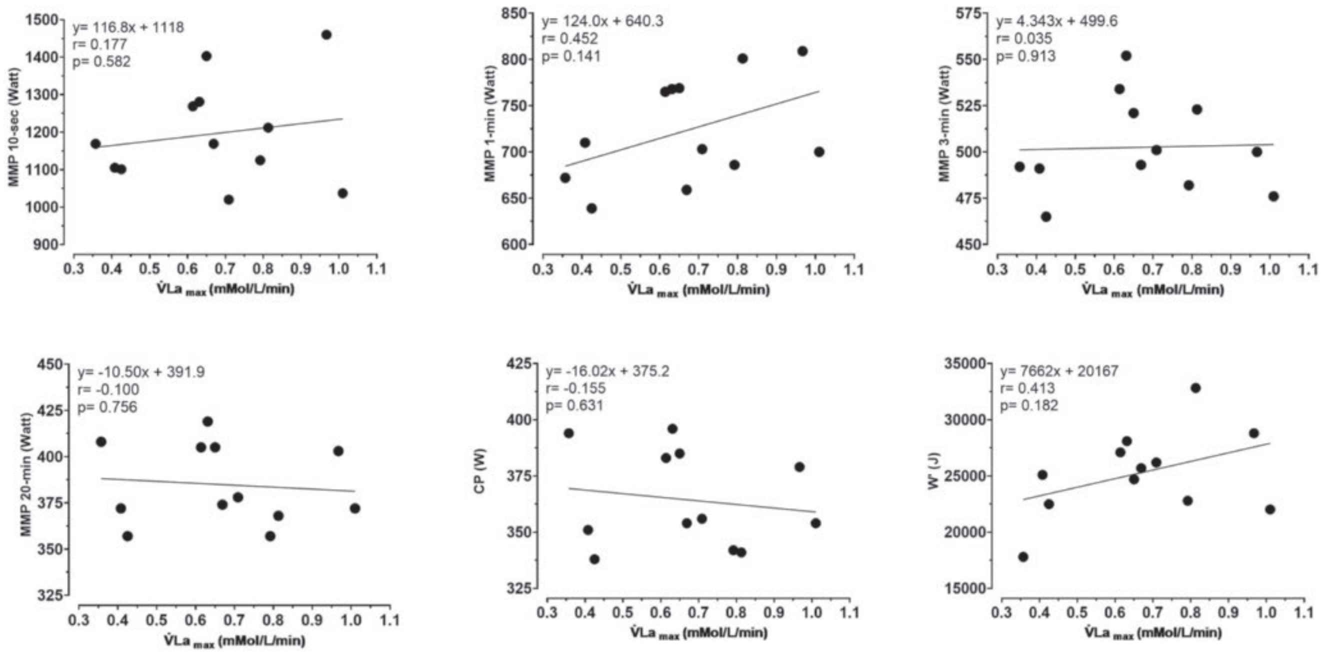

Fig. 4 Linear regression analysis of $\dot{V}La_{max}$ and outdoor tested mean maximal power output of different durations (MMP10-second, MMP 1-minute, MMP 3-minute, and MMP 20-minute) and calculated threshold parameters (CP and W′).

applied in elite cyclists, also due to the laborious protocol to assess MLSS. CP is a metric more widely applied within the practice of elite cycling. Hence, within our current research, we aimed to compare modelled MLSS to CP, a more practically applied metric. While significant correlations between experimentally measured MLSS via a 30-minute constant load test and CP[15, 16, 27, 28] have been reported previously, the present study is the first to show the correlation between mathematically modelled MLSS and field-based CP. Although the power output at experimentally measured MLSS correlated well with CP in previous research, it was modestly but consistently lower than CP.[29] In the current study, we confirm that there is slight bias between CP and modelled MLSS on a group level. However, the difference between modelled MLSS and CP in the current study ranged from − 14 to + 37 W. In comparison with the range reported by Hauser et al., in a group of well-trained amateur cyclists (− 20 to 50 W),[14] the range in the current study is slightly smaller, but this could be due to a more homogenous population.

What must be considered is the chosen test duration for the $\dot{V}La_{max}$ test might be suboptimal to capture the true peak in the lactate accumulation rate. As recent research has shown that higher $\dot{V}La_{max}$ values have been observed with a test duration of 10 seconds in comparison with a test duration of 15 seconds.[30] An under estimation of the $\dot{V}La_{max}$ will lead to an overestimation of modelled MLSS, and in the current study it might result in a smaller difference than the true difference.

Additionally, the CP has only been measured by two maximal tests in the field. The protocol was chosen for practical reasons and applicability of the test results to align with existing protocols of the professional cycling team. In a previous study by Maturana et al., it is shown that the method chosen to calculate CP in the current study shows a trivial difference compared to the reference CP modelling by the hyperbolic model on the basis of five maximal tests of different durations[31] and it is not likely that the conclusion of the current research would be different when another CP testing protocol was used.

While it is a wide range in the individual difference of modelled MLSS and CP, especially considering that practitioners working with high level pro cyclists will be operating with much smaller margins of improvement and change then observed in this study. The mathematical model seems to be able to predict sustainable power output to an extend that could be deemed impressive on a group level, especially considering the complex physiology underlying sustainable power output. However, the large individual differences seen in the predictive ability would argue against the use of modelled MLSS by practitioners working with elite pro cyclists.

Relationship between the laboratory tests and field tests

The correlation analysis between the laboratory tests and field tests revealed significant correlations between $\dot{V}O_{2max}$ and MMP over 3 minutes, 20 minutes and CP. This is in line with previous research that showed significant correlations between $\dot{V}O_{2max}$ and CP[32] and between $\dot{V}O_{2max}$ and 20-minute MMP output[6, 33] and confirms the contribution of aerobic metabolism for efforts of longer duration.

In contrast to previous research showing significant correlations between power output during the 15 second $\dot{V}La_{max}$ test and $\dot{V}La_{max}$ itself,[22] the current study in pro cyclists did not observe any correlation of $\dot{V}La_{max}$ with MMP output in field of short durations (MMP 1-min and MMP 10-seconds) or with the capacity of work which can be performed above CP (W′).

The absence of correlation between $\dot{V}La_{max}$ and MMP output of short durations in field may originate from the matter that during a short-duration sprint test like the $\dot{V}La_{max}$ test, a substantial fraction of the energy required originates from the phosphocreatine pathway, or alactic power production, and this fraction can differ substantially between individuals.[20] During 15-seconds $\dot{V}La_{max}$ test, for example, it was shown that only 35 % of energy was produced via glycolysis.[34] For durations beyond 15 seconds, the energy produced from aerobic sources will increase substantially; for 60 seconds, this is estimated to be ~45 % of total energy production.[35] As mentioned before, the current approach in assessing the maximal glycolytic rate using the $\dot{V}La_{max}$ has many limitations. To start with the applied protocol of the $\dot{V}La_{max}$ test, blood lactate is sampled to indirectly estimate muscle lactate production and consumption. Rather it is an accumulation rate in the lactate distribution volume, which is both influenced by production and elimination rates.[36] The combination of both aspects contributes to an absence of observable relationship between $\dot{V}La_{max}$ and any of the outdoor performance measures.

Limitations of the study design

A main limitation of the study is that the sample size was limited and constrained by the availability of riders to fulfil all required testing. It must be acknowledged that results of the current study must be taken as descriptive of a group of highly trained cyclists rather than hypothesis confirming.

Due to difficulties in logistics and training scheduling in this population, the time frame in which the testing took place for each participant was rather long. It must be said that the performance measure of the main outcome has been measured during a period of maximally 10 days. At the same time, it should be recognised that the period of examination was too short to anticipate (de) training effects to interfere. Influences of sickness and performance lowering circumstances can, however, not be excluded. Needless to say, if a participant was ill on the morning of the test, testing has not been performed as scheduled but postponed. Additionally, circumstances (like environmental factors) of testing could not be fully standardized, due to logistical reasons. This suboptimal standardisation still leaves open the options for lower intra- and interindividual variation, and hence reduced outcome variation and improved predictability.

Practical applications

This study shows that the mathematical model originally published by Mader and Heck has a level of merit in predicting sustainable power output in highly trained male pro cyclists. Furthermore, this study shows how the parameters used in modelled MLSS relate to field-based performance measures. Especially on group level, modelled MLSS is well correlated to outdoor CP; however, in individual cases, the variation is rather wide. Therefore, the use of the model is limited in individualised training intensity zone setting and it must be stretched that the individual variation between laboratory test data and outdoor tested mathematical threshold models, like CP, can vary substantially.

Nevertheless, this should not rule out potential valuable practical insights that can be gained from the use of modelled MLSS and its estimates of 'aerobic' and 'anaerobic' contributions to sustainable power output. As shown previously, different training protocols can be similarly effective in raising MLSS while either lowering $\dot{V}La_{max}$ by an endurance training program or heightening $\dot{V}O_{2max}$ by a sprint interval training program.[37] Conventional outdoor testing only gives limited insights into how a combined contribution of aerobic and anaerobic metabolic pathways lead to a maximal mean power output or achievement of various training intensities. The research by Hommel et al.[37] and the current study showcase the validity of the mathematical construct behind modelled MLSS and the relationship with field-based performance measures. Adding laboratory measures of modelled MLSS and the insights behind modelled MLSS as a compliment to field-based threshold testing can give a more accurate representation of the metabolic profile of a rider. By applying the insights of modelled MLSS, a more targeting training approach can be taken.

Conclusions

From the comparison of modelled MLSS to the field-based threshold of CP in a group of highly trained male cyclists, it can be concluded that the mathematical model seems to be able to predict sustainable power output to an extend that could be deemed good on a group level, especially considering the complex physiology underlying sustainable power output. Nevertheless, the large individual differences seen in the predictive ability would argue against the use of modelled MLSS by practitioners working with elite cyclists.

Furthermore, it should be examined if changes by training of the $\dot{V}La_{max}$ without changes in the $\dot{V}O_{2max}$, or vice versa, are translated into meaningful differences in outdoor maximal mean power values.

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Statements and Additional Information

Conflict of Interest The authors declare that they have no conflict of interest.

Contributors' Statement Ivo Servatius Johannes Habets: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, and writing – review and editing. Jelle de Jong: investigation, resources, and writing – review and editing. Sjors Groot: investigation, resources, and writing – review and editing. Matthijs K. C. Hesselink: conceptualization, investigation, methodology, supervision, writing – original draft, and writing – review and editing. Dajo Sanders: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, supervision, validation, writing – original draft, and writing – review and editing.

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