Calculation of the metabolic demands of a successful cycling world-hour record by a validated mathematical model

Robberechts Ruben, [1] **Poffé Chiel,** [1] **Van Schuylenbergh Reinout** [2 3]

[1]Faculty of Rehabilitation Sciences, Hasselt University, Agoralaan 3590 Diepenbeek (Belgium)
[2]KU Leuven, Department of Movement Sciences, Tervuursevest 101, 3001 Leuven (Belgium)
[3]INSCYD GmbH, Salenstein (Switzerland)

World hour record | Cycling | Metabolic profile | VLa$_{max}$ | Substrate utilization | Mathematical modelling

Headline

The cycling world hour record (WHR) is one of the most mythical and prestigious cycling performances. For one hour, cyclists aim to cover the longest distance possible on a cycling velodrome. Many of the most successful and legendary cyclists, such as Fausto Coppi, Jacques Anquetil, Francesco Moser, Eddy Merckx, Miguel Indurain or Bradley Wiggins have focused on improving the WHR during their careers. Despite the increasing scientific information on professional cycling performance (1–4), scientific data on the WHR is rather limited.

Aim

Bassett and colleagues used a mathematical model to compare calculated data with empirical data from the WHR 1967-1996 (5). They concluded that since 1967, about 60% of the improvement in the hour record distance has come from aerodynamic improvements and about 40% from higher power outputs. The authors estimated that for future attempts a minimum of 440 W at sea level would be required. Padilla and colleagues described the physiological profile and aerodynamics of an elite road cyclist leading to a successful WHR attempt (6). Based on their model, they calculated an average power output during the WHR of 510 W (~6.3 W·kg^{-1}). However, the metabolic requirements for a successful WHR are not disclosed by these average power outputs alone. In other words, the contribution of aerobic and anaerobic energy pathways during a WHR is not yet disclosed. Such improved understanding of the lactate dynamics and aerobic/anaerobic energy contributions of a successful WHR attempt could be used to optimize the training process for future athletes attempting to improve the WHR. Therefore, the aim of the current study is to compute the lactate dynamics and energy contributions of a successful WHR attempt based on previously published data (6).

Methods

The data for this study are retrieved from the paper of Padilla et al (6) (table 1) and are used to feed a mathematical model of muscle metabolism (INSCYD GmbH, version 2.0, Salenstein, Switzerland). This model has been validated for the determination of $\dot{V}O_{2max}$ and MLSS in well-trained cyclists (7,8). Individual data used to run these calculations were: sex, body mass, $\dot{V}O_{2max}$, gross efficiency (GE) and MLSS. Body composition was set at 9% body fat, which was not reported in the study of Padilla et al (6) but assessed based on literature data in professional cyclists (9,10). All other settings in the software such as detailed body composition was kept at default values as preset in the software (table 2).

As the power at MLSS is a function of the maximal oxygen uptake ($\dot{V}O_{2max}$) and the maximal glycolytic rate (VLa$_{max}$) (11–13) and using the power output at a BLC of 4 mmol·l^{-1} (LT4) as an approximation for the MLSS (14), VLa$_{max}$ could be calculated from the available data. Based on the measured $\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1}) and the calculated VLa$_{max}$ (mmol·l^{-1}·s^{-1}), the aerobic and anaerobic energy contribution, and the lactate accumulation rate (mmol·l^{-1}·min^{-1}) at WHR power (510 W) was calculated.

Table 1. Data retrieved from Padilla et al (2000).

Height (cm)	Weight (kg)	$\dot{V}O_{2max}$ (l·min^{-1})	LT4 (W)	GE (%)	WHR PO (W)	WHR BLC
188	81	6.4	505	26	510	5.2

Table 2. Applied default settings in the INSCYD software for body composition based on a body fat percentage of 9%.

Body water (% body mass)	Total muscle mass (% body mass)	Muscle mass used (% muscle mass)	Lactate distribution space (% body mass)
68.88	42.42	65	50.63

Results

Based on the above-mentioned data and methodology, the calculated VLa_{max} was 0.38 $mmol \cdot l^{-1} \cdot s^{-1}$. Lactate accumulation rate at the average PO during the WHR was 0.06 $mmol \cdot l^{-1} \cdot min^{-1}$ resulting in a total lactate accumulation of 3.6 $mmol \cdot l^{-1}$. Given a pre-exercise BLC in the range of 0.8-1.3 $mmol \cdot l^{-1}$, this would result in a post WHR BLC of 4.4-4.9 $mmol \cdot l^{-1}$ which approximates the measured BLC (5.2 $mmol \cdot l^{-1}$) 3 minutes after the WHR attempt. PO at 4 $mmol \cdot l^{-1}$ lactate was calculated at 87.2% of $\dot{V}O_{2max}$ and approximated the measured value (88.2%). The calculated energy contribution based on the average PO during WHR amounted 8.2% from anaerobic and 91.8% from aerobic energy metabolism with a corresponding carbohydrate utilization of $\sim$405$g \cdot h^{-1}$.

The effect of the typical error in $\dot{V}O_{2max}$ ($\pm$2.5 $ml \cdot kg^{-1} \cdot min^{-1}$) (15) and VLa_{max} ($\pm$ 0.05 $mmol \cdot l^{-1} \cdot min^{-1}$) (16) on the calculated lactate concentration after the WHR is shown in table 3. The effect of changes in body fat percentage on the lactate concentration after the WHR is shown in table 4.

Table 3. The effect of the typical errors in $\dot{V}O_{2max}$($\pm$2.5 $ml \cdot kg^{-1} \cdot min^{-1}$) and VLa_{max} ($\pm$0.05 $mmol \cdot l^{-1} \cdot s^{-1}$) in a subject with body mass 81kg and 9% body fat on the calculation of the MLSS, the BLA and BLC at WHR PO.

$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	VLa_{max} ($mmol \cdot l^{-1} \cdot s^{-1}$)	$MLSS_{INSCYD}$ (W)	WHR BLA ($mmol \cdot l^{-1} \cdot min^{-1}$)	WHR BLC ($mmol \cdot l^{-1}$)	Plausible solution
76.51	0.33	499	0.19	12.2-12.7	(1)
	0.38	487	0.39	24.2-24.7	(1)
	0.43	476	0.57	35-35.5	(1)
79.01	0.33	517	-0.12	(4)	(2)
	0.38	505	0.06	4.4-4.9	(3)
	0.43	495	0.24	15.2-15.7	(1)
81.51	0.33	536	-0.39	(4)	(2)
	0.38	525	-0.22	(4)	(2)
	0.43	514	-0.06	(4)	(2)

1. No plausible solution. Difference with measured WHR BLC $>$ 1 $mmol \cdot l^{-1}$.
2. No plausible solution. No lactate accumulation.
3. Plausible solution. Difference with measured WHR BLC $<$ 1 $mmol \cdot l^{-1}$.
4. No lactate accumulation. BLC at PO $<$ MLSS generally is in the range of 2-4 $mmol \cdot l^{-1}$.

Table 4. The effect of body fat percentage on the calculation of the MLSS, the BLA and BLC at WHR PO in a subject with body mass 81kg, $\dot{V}O_{2max}$ 79.01 $ml \cdot kg^{-1} \cdot min^{-1}$ and VLa_{max} 0.38 $mmol \cdot l^{-1} \cdot s^{-1}$.

Body fat percentage	$MLSS_{INSCYD}$ (W)	WHR BLA ($mmol \cdot l^{-1} \cdot min^{-1}$)	WHR BLC ($mmol \cdot l^{-1}$)	Plausible solution
8%	505	0.08	5.6-6.1	(3)
9%	505	0.06	4.4-4.9	(3)
10%	507	0.06	4.4-4.9	(3)

1. No plausible solution. Difference with measured WHR BLC $>$ 1 $mmol \cdot l^{-1}$.
2. No plausible solution. No lactate accumulation.
3. Plausible solution. Difference with measured WHR BLC $<$ 1 $mmol \cdot l^{-1}$.

Discussion

This study investigated the physiological profile of a WHR cyclist, the aerobic and anaerobic energy contribution, and the lactate accumulation dynamics during a successful WHR attempt. The data published by Padilla et al (6) was used to calculate the maximal glycolytic rate (VLa_{max}) of 0.38 $mmol \cdot l^{-1} \cdot s^{-1}$. Recently, The VLa_{max}, as an estimate of the maximal glycolytic power, has received more attention in the scientific literature (13). Descriptive data of VLa_{max} values in elite cyclists based on a validated VLa_{max} protocol (17) are still scarce. Yang and colleagues observed VLa_{max} values of 0.97$\pm$0.18 $mmol \cdot l^{-1} \cdot s^{-1}$ in elite cycle track sprinters (18). In endurance athletes, VLa_{max} values are typically in the range of 0.3-0.7 $mmol \cdot l^{-1} \cdot s^{-1}$ (17,19–21) and the calculated value in this study corresponds with these observations. Relatively low VLa_{max} values seems to be favorable for a WHR performance as it allows higher PO in physiological steady state conditions (13,22,23). However, a too low VLa_{max} value (e.g., $<$ 0.2 $mmol \cdot l^{-1} \cdot s^{-1}$) might compromise the PO needed for the standing start ($\sim$1.000W) and causes a rapid lactate accumulation and muscular fatigue at power outputs above MLSS. It can be speculated that the calculated VLa_{max} value in this study is optimal to accommodate the specific PO requirements during a WHR performance.

The cyclist in this study was one of the most successful time-trial and GC grand tour riders of his generation, winning the time-trial World title once, the Tour de France 5 times and the Giro d'Italia 2 times. His $\dot{V}O_{2max}$ value ($\sim$79 $ml \cdot kg^{-1} \cdot min^{-1}$) was around 5 $ml \cdot kg^{-1} \cdot min^{-1}$ lower than observed in another grand tour winner (9) and lower as what is recognized as the upper limit of oxygen uptake in world-class male cyclists ($\sim$90 $ml \cdot kg^{-1} \cdot min^{-1}$) (24). The extremely high workloads at a metabolic steady state ($\sim$505 W) in this cyclist can be explained by his high maximal oxygen uptake, an extraordinary mechanical efficiency (9,25) and relatively low glycolytic power (12,13). The observed gross efficiency (GE) of 26% and the calculated VLa_{max} of 0.38 $mmol \cdot l^{-1} \cdot s^{-1}$ fits in this reasoning.

Based on the $\dot{V}O_{2max}$, GE and VLa_{max} data, aerobic and anaerobic energy contribution, and the post WHR BLC could be calculated using a commercially available physiological performance model. According to these calculations, ~92% of the energy contribution during the WHR came from aerobic metabolism and ~8% from anaerobic metabolism. In the scientific literature, not much information is available on energy contributions in maximal efforts of ~1h duration in elite cyclists. It has been repeatedly demonstrated that the longer the event, the higher the aerobic energy contribution with an equal contribution from the aerobic and anaerobic energy systems for maximal efforts of around 75 seconds (26,27). Foster et al demonstrated in a sample of competitive road cyclists that the absolute anaerobic energy contribution (kJ) only slightly increased in maximal cycling efforts of 500m-3000m (corresponding exercise times ~40-300s). Consequently, the relative contribution of aerobic energy increases with increasing exercise duration and amounted ~70% for an exercise duration of ~5 min (26). In endurance athletes as in the case of this study, the aerobic energy contribution for a fixed exercise duration is higher compared to sprint athletes (27). The high $\dot{V}O_{2max}$ and GE and relatively low VLa_{max} values reported in this study are indicative for an athlete with a type I dominant muscle fiber typology (13,28) favoring aerobic metabolism. Some limitations of this study should be acknowledged. The $\dot{V}O_{2max}$ was based on historical test data and this value was not confirmed with breathing gas data during a maximal laboratory test in the days leading up the WHR attempt. In general, $\dot{V}O_{2max}$ values are relatively stable in elite athletes during the racing season (29), but it cannot be excluded that the actual $\dot{V}O_{2max}$ was somewhat different from the value that has been used in the simulations. Therefore, we simulated the effect of a lower and higher $\dot{V}O_{2max}$ (± 2.5 $ml \cdot kg^{-1} \cdot min^{-1}$) on the WHR BLC and blood lactate accumulation rate. According to our calculations, a lower $\dot{V}O_{2max}$ results in an increased lactate accumulation rate and in BLC that are significantly higher than the measured BLC. A higher $\dot{V}O_{2max}$ results in a PO at MLSS that is higher than the average PO during the WHR. This is possible from a physiological point of view, but nevertheless not a likely situation during an all-out effort of 1-h duration. Moreover, this would cause a BLC that is lower than the measured BLC after the WHR.

Secondly, to be able to calculate VLa_{max}, the PO at LT4 was used to reflect MLSS. Despite relatively high correlations between LT4 and MLSS in well-trained cyclists, on the individual athlete, the bias between these 2 markers of lactate steady state can be quite large (14,30). Also, PO at LT4 is depended on the applied test protocol (30) and consequently, this exercise intensity cannot be used as a marker for MLSS in all athletes and in all test conditions. Future research should focus on the application of golden standard methodologies to quantify the metabolic profile of WHR cyclists to further increase our understanding of the metabolic demand of this mythical cycling event.

To summarize, the findings of the current explorative study indicate that the physiological profile of a successful WHR cyclist can be described by a high aerobic power (~ 79 $ml \cdot kg^{-1} \cdot min^{-1}$), low glycolytic power (~0.38 $mmol \cdot l^{-1} \cdot s^{-1}$) and excellent cycling efficiency (~26%). This profile is typically seen in endurance athletes with a type I muscle fiber dominant typology (28,31). This information can be valuable for coaches and athletes to optimize training for a WHR attempt.

Practical implications

- A successful WHR requires an extremely high aerobic fitness, mechanical efficiency and a relatively low glycolytic power
- Training strategies for the WHR should focus on maximizing aerobic power and optimizing glycolytic power.
- The mathematical model used in this case study can be utilized to perform performance projections based on a given or desired physiological profile.

Conflicts of interest

Reinout Van Schuylenbergh is consultant for INSCYD GmbH. No funding was received for this research.

Data availability

The data that support the findings of this study are shown in this manuscript.

References

1. Atkinson G, Davison R, Jeukendrup A, Passfield L. Science and cycling: current knowledge and future directions for research. Journal of Sports Sciences [Internet]. 2003 Sep [cited 2023 Jul 5];21(9):767–87. Available from: http://www.tandfonline.com/doi/abs/10.1080/0264041031000102097

2. Valenzuela PL, Muriel X, Van Erp T, Mateo-March M, Gandia-Soriano A, Zabala M, et al. The Record Power Profile of Male Professional Cyclists: Normative Values Obtained From a Large Database. International Journal of Sports Physiology and Performance [Internet]. 2022 May 1 [cited 2023 Jul 5];17(5):701–10. Available from: https://journals.humankinetics.com/view/journals/ijspp/17/5/article-p701.xml

3. Van Erp T, Sanders D. Demands of professional cycling races: Influence of race category and result. European Journal of Sport Science [Internet]. 2021 May 4 [cited 2023 Jul 9];21(5):666–77. Available from: https://www.tandfonline.com/doi/full/10.1080/17461391.2020.1788651

4. Van Erp T, Hoozemans M, Foster C, De Koning JJ. Case Report: Load, Intensity, and Performance Characteristics in Multiple Grand Tours. Medicine & Science in Sports & Exercise [Internet]. 2020 Apr [cited 2023 Jul 10];52(4):868–75. Available from: https://journals.lww.com/10.1249/MSS.0000000000002210

5. Bassett DRJ, Kyle CR, Passfield L, Broker JP, Burke E. Comparing cycling world hour records, 1967–1996: modeling with empirical data. Medicine & Science in Sports & Exercise [Internet]. 1999;31(11). Available from: https://journals.lww.com/acsm-msse/Fulltext/1999/11000/Comparing_cycling_world_hour_records,_1967_1996_.25.aspx

6. Padilla S, Mujika I, Angulo F, Goiriena JJ. Scientific approach to the 1-h cycling world record: a case study. Journal of Applied Physiology [Internet]. 2000 Oct 1 [cited 2023 Apr 17];89(4):1522–7. Available from: https://www.physiology.org/doi/10.1152/jappl.2000.89.4.1522

7. 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 Cycling [Internet]. 2022 Jun 30 [cited 2023 Apr

4];11(1):30–8. Available from: `https://www.jsc-journal.com/index.php/JSC/article/view/725`

8. 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 [Internet]. 2024 May 7 [cited 2024 Jun 19];6:1376876. Available from: `https://www.frontiersin.org/articles/10.3389/fspor.2024.1376876/full`

9. Bell PG, Furber MJW, Van Someren KA, Antón-Solanas A, Swart J. The Physiological Profile of a Multiple Tour de France Winning Cyclist. Medicine & Science in Sports & Exercise [Internet]. 2017 Jan [cited 2023 Apr 17];49(1):115–23. Available from: `https://journals.lww.com/00005768-201701000-00014`

10. Lucia A, Hoyos J, Chicharro JL. Physiology of Professional Road Cycling: Sports Medicine [Internet]. 2001 [cited 2023 Aug 14];31(5):325–37. Available from: `http://link.springer.com/10.2165/00007256-200131050-00004`

11. Mader A. Anaerobic threshold (AT) as determined by VO2max and Vlamax of the working muscle mass of the human body - an update of the theoretical concept. In Rome: European College of Sport Science; 1999. p. 14.

12. Mader A. Glycolysis and oxidative phosphorylation as a function of cytosolic phosphorylation state and power output of the muscle cell. Eur J Appl Physiol [Internet]. 2003 Jan [cited 2023 Apr 4];88(4):317–38. Available from: `http://link.springer.com/10.1007/s00421-002-0676-3`

13. 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 [Internet]. 2022 Jul 22 [cited 2023 Apr 4];13:899670. Available from: `https://www.frontiersin.org/articles/10.3389/fphys.2022.899670/full`

14. Hauser T, Adam J, Schulz H. Comparison of Selected Lactate Threshold Parameters with Maximal Lactate Steady State in Cycling. Int J Sports Med [Internet]. 2013 Nov 13 [cited 2023 Jul 7];35(06):517–21. Available from: `http://www.thieme-connect.de/DOI/DOI?10.1055/s-0033-1353176`

15. Vickers J, Ross R. Measurement Error in Maximal Oxygen Uptake Tests: [Internet]. Fort Belvoir, VA: Defense Technical Information Center; 2003 Nov [cited 2023 Apr 17]. Available from: `http://www.dtic.mil/docs/citations/ADA454282`

16. Meixner B, Nusser V, Koehler K, Sablain M, Boone J, Sperlich B. Reliability of power output, maximal rate of capillary blood lactate accumulation, and phosphagen contribution time following 15-s sprint cycling in amateur cyclists. Physiological Reports [Internet]. 2024 May [cited 2024 Sep 19];12(10):e16086. Available from: `https://physoc.onlinelibrary.wiley.com/doi/10.14814/phy2.16086`

17. Weber S. Calculation of performance-determining parameters of metabolic activity at the cellular level by means of cycle ergometry [Berechnung leistungsbestimmender Parameter der metabolischen Aktivität auf zellulärer Ebene mittels fahrradergometrischer Untersuchungen]. [Dipon Diplomarb.]. [Köln.]: Dtsch. Sporthochsch.; 2003.

18. Yang WH, Park SY, Kim T, Jeon HJ, Heine O, Gehlert S. A modified formula using energy system contributions to calculate pure maximal rate of lactate accumulation during a maximal sprint cycling test. Front Physiol [Internet]. 2023 Apr 13 [cited 2023 Jul 7];14:1147321. Available from: `https://www.frontiersin.org/articles/10.3389/fphys.2023.1147321/full`

19. Ji S, Sommer A, Bloch W, Wahl P. Comparison and Performance Validation of Calculated and Established Anaerobic Lactate Thresholds in Running. Medicina [Internet]. 2021 Oct 16 [cited 2023 Apr 4];57(10):1117. Available from: `https://www.mdpi.com/1648-9144/57/10/1117`

20. Quittmann OJ, Abel T, Vafa R, Mester J, Schwarz YM, Strüder HK. Maximal lactate accumulation rate and post-exercise lactate kinetics in handcycling and cycling. European Journal of Sport Science [Internet]. 2021 Apr 3 [cited 2023 Apr 17];21(4):539–51. Available from: `https://www.tandfonline.com/doi/full/10.1080/17461391.2020.1756420`

21. Schünemann F, Park SY, Wawer C, Theis C, Yang WH, Gehlert S. Diagnostics of VLamax and Glycolytic Energy Contribution Indicate Individual Characteristics of Anaerobic Glycolytic Energy Metabolism Contributing to Rowing Performance. Metabolites [Internet]. 2023 Feb 21 [cited 2023 Jul 10];13(3):317. Available from: `https://www.mdpi.com/2218-1989/13/3/317`

22. Bleicher J A, Mader, A, Mester. Zur Interpretation von Laktatleistungskurven - experimentelle Ergebnisse mit computergestützten Nachberechnungen. Spectrum der Sportwissenschaften. 1999;11(1):71–83.

23. Nolte S, Quittmann OJ, Meden V. Simulation of Steady-State Energy Metabolism in Cycling and Running [Internet]. 2022 Sep [cited 2023 Apr 4]. (Sportrxiv). Available from: `https://sportrxiv.org/index.php/server/preprint/view/110/version/238`

24. Haugen T, Paulsen G, Seiler S, Sandbakk Ø. New Records in Human Power. International Journal of Sports Physiology and Performance [Internet]. 2018 Jul 1 [cited 2023 Jul 7];13(6):678–86. Available from: `https://journals.humankinetics.com/view/journals/ijspp/13/6/article-p678.xml`

25. Lucia A, Hoyos JS, Rez MP, Santalla A, Chicharro JL. Inverse relationship between $\dot{V}O_{2\text{max}}$ and economy/efficiency in world-class cyclists. Medicine and Science in Sports and Exercise. 2002;34(12):2079–85.

26. Foster C, De Koning JJ, Hettinga FJ, Lampen J, Dodge C, Bobbert M, et al. Effect of Competitive Distance on Energy Expenditure During Simulated Competition. Int J Sports Med [Internet]. 2004 Apr [cited 2023 Aug 15];25(3):198–204. Available from: `http://www.thieme-connect.de/DOI/DOI?10.1055/s-2003-45260`

27. Gastin PB. Energy System Interaction and Relative Contribution During Maximal Exercise: Sports Medicine [Internet]. 2001 [cited 2023 Jul 7];31(10):725–41. Available from: `http://link.springer.com/10.2165/00007256-200131100-00003`

28. Coyle E, Sidossis L, Horowitz J, Beltz john. Cycling efficiency is related to the percentage of Type I muscle fibers. Medicine & Science in Sports & Exercise [Internet]. 1992;24(7):782–8. Available from: `https://journals.lww.com/acsm-msse/Fulltext/1992/07000/Cycling_efficiency_is_related_to_the_percentage_of.8.aspx`

29. Lucía A, Hoyos J, Pardo J, Chicharro JL. Metabolic and Neuromuscular Adaptations to Endurance Training in Professional Cyclists. A Longitudinal Study. JJP [Internet]. 2000 [cited 2023 Aug 15];50(3):381–8. Available from: `http://www.jstage.jst.go.jp/article/jjphysiol/50/3/50_3_381/_article`

30. Van Schuylenbergh R, Vanden Eynde B, Hespel P. Correlations Between Lactate and Ventilatory Thresholds and the Maximal Lactate Steady State in Elite Cyclists. Int J Sports Med [Internet]. 2004 Aug [cited 2023 Apr 4];25(6):403–8. Available from: `http://www.thieme-connect.de/DOI/DOI?10.1055/s-2004-819942`

31. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions: Factors that make champions. The Journal of Physiology [Internet]. 2008 Jan 1 [cited 2023 Jul 5];586(1):35–44. Available from: `http://doi.wiley.com/10.1113/jphysiol.2007.143834`