



# Kent Academic Repository

Wong, Stephen, Burnley, Mark, Mauger, Alexis R., Fenghua, Sun and Hopker, James G. (2023) *Functional threshold power is not a valid marker of the maximal metabolic steady state*. *Journal of Sports Sciences*, 40 (23). pp. 2578-2584. ISSN 0264-0414.

## Downloaded from

<https://kar.kent.ac.uk/100046/> The University of Kent's Academic Repository KAR

## The version of record is available from

<https://doi.org/10.1080/02640414.2023.2176045>

## This document version

Publisher pdf

## DOI for this version

## Licence for this version

CC BY-NC-ND (Attribution-NonCommercial-NoDerivatives)

## Additional information

## Versions of research works

### Versions of Record

If this version is the version of record, it is the same as the published version available on the publisher's web site. Cite as the published version.

### Author Accepted Manuscripts

If this document is identified as the Author Accepted Manuscript it is the version after peer review but before type setting, copy editing or publisher branding. Cite as Surname, Initial. (Year) 'Title of article'. To be published in **Title of Journal**, Volume and issue numbers [peer-reviewed accepted version]. Available at: DOI or URL (Accessed: date).

### Enquiries

If you have questions about this document contact [ResearchSupport@kent.ac.uk](mailto:ResearchSupport@kent.ac.uk). Please include the URL of the record in KAR. If you believe that your, or a third party's rights have been compromised through this document please see our [Take Down policy](https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies) (available from <https://www.kent.ac.uk/guides/kar-the-kent-academic-repository#policies>).



# Functional threshold power is not a valid marker of the maximal metabolic steady state

Stephen Wong, Mark Burnley, Alexis Mauger, Sun Fenghua & James Hopker

To cite this article: Stephen Wong, Mark Burnley, Alexis Mauger, Sun Fenghua & James Hopker (2022) Functional threshold power is not a valid marker of the maximal metabolic steady state, Journal of Sports Sciences, 40:23, 2578-2584, DOI: [10.1080/02640414.2023.2176045](https://doi.org/10.1080/02640414.2023.2176045)

To link to this article: <https://doi.org/10.1080/02640414.2023.2176045>



© 2023 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.



Published online: 20 Feb 2023.



Submit your article to this journal [↗](#)



Article views: 553








View related articles [↗](#)



View Crossmark data [↗](#)

## Functional threshold power is not a valid marker of the maximal metabolic steady state

Stephen Wong <sup>a</sup>, Mark Burnley <sup>a</sup>, Alexis Mauger <sup>a</sup>, Sun Fenghua <sup>b</sup> and James Hopker <sup>a</sup>

<sup>a</sup>School of Sport and Exercise Sciences, University of Kent, Chipperfield Building, Canterbury Campus, Canterbury, UK; <sup>b</sup>Department of Health and Physical Education, Education University of Hong Kong, Tai Po, Hong Kong

### ABSTRACT

Functional Threshold Power (FTP) has been considered a valid alternative to other performance markers that represent the upper boundary of the heavy intensity domain. However, such a claim has not been empirically examined from a physiological perspective. This study examined the blood lactate and  $\text{VO}_2$  response when exercising at and 15 W above the FTP ( $\text{FTP}_{+15\text{W}}$ ). Thirteen cyclists participated in the study. The  $\text{VO}_2$  was recorded continuously throughout FTP and  $\text{FTP}_{+15\text{W}}$ , with blood lactate measured before the test, every 10 minutes and at task failure. Data were subsequently analysed using two-way ANOVA. The time to task failure at FTP and  $\text{FTP}_{+15\text{W}}$  were  $33.7 \pm 7.6$  and  $22.0 \pm 5.7$  minutes ( $p < 0.001$ ), respectively. The  $\text{VO}_{2\text{peak}}$  was not attained when exercising at  $\text{FTP}_{+15\text{W}}$  ( $\text{VO}_{2\text{peak}}$ :  $3.61 \pm 0.81$  vs  $\text{FTP}_{+15\text{W}}$   $3.33 \pm 0.68$   $\text{L}\cdot\text{min}^{-1}$ ,  $p < 0.001$ ). The  $\text{VO}_2$  stabilised during both intensities. However, the end test blood lactate corresponding to FTP and  $\text{FTP}_{+15\text{W}}$  was significantly different ( $6.7 \pm 2.1$  mM vs  $9.2 \pm 2.9$  mM;  $p < 0.05$ ). The  $\text{VO}_2$  response corresponding to FTP and  $\text{FTP}_{+15\text{W}}$  suggests that FTP should not be considered a threshold marker between heavy and severe intensity.

### ARTICLE HISTORY

Received 2 September 2022  
Accepted 30 January 2023

### KEYWORDS

Cycling; functional threshold power; oxygen kinetics;  $\text{VO}_2$  slow component; exercise intensity domains

### Introduction

Over recent years, field-based testing methods for assessing athletic endurance performance potential have become more popular. This has been facilitated by the progress in micro-technologies such as the cycle computer and power metre, which are now essential components for most cyclists. One commonly used field-based test for assessing cycling performance potential is the Functional Threshold Power (FTP) test (Allen & Coggan, 2006; 2010). The FTP is the highest power output a cyclist can maintain in a quasi-steady state for one hour (Allen & Coggan, 2010). Determining the power output corresponding to FTP originally required cyclists to perform a maximal effort trial over one hour ( $\text{FTP}_{60}$ ), but it was deemed impractical to conduct this test regularly. Thus, the determination protocol was modified to require an individual to perform a 20 minute maximal effort time trial (TT) 95% of the mean power output subsequently calculated for the intensity corresponding to FTP ( $\text{FTP}_{20}$ ; Inglis et al., 2019; Morgan et al., 2019). Indeed, a strong correlation has been shown between the work rate corresponding to  $\text{FTP}_{20}$  and  $\text{FTP}_{60}$  ( $r = 0.88$ ; Borszcz et al., 2018). However, it has been questioned whether the power output from  $\text{FTP}_{20}$  and  $\text{FTP}_{60}$  can be considered interchangeable on an individual basis, despite no statistically significant differences between the two on a group basis (Borszcz et al., 2018). Moreover, previous research has shown that cyclists often fail to maintain the work rate corresponding to  $\text{FTP}_{20}$  for one hour (Borszcz et al., 2018; Sitko et al., 2022).

The FTP has also been proposed to be a surrogate of some well-known performance markers representing the maximal

oxidative steady state or the maximal metabolic steady state (MMSS). For example, critical power (CP; Jones et al., 2019) and maximal lactate steady state (MLSS) (Dotan, 2022) because exercise sustained at intensities slightly greater than FTP ( $> 106\%$  of FTP) is suggested to result in  $\text{VO}_{2\text{max}}$  attainment (Allen & Coggan, 2010). However, unlike the aforementioned CP and MLSS, there is a paucity of research investigating the validity of FTP. The case for the use of FTP can be made based on findings from Coyle et al. (1991), who demonstrate that a 1-hour laboratory performance test was highly correlated with the actual road racing 40 km TT performance ( $r = -0.88$ ,  $p < 0.001$ ) (Coyle et al., 1991). Thus, a more rigorous scientific examination is required before making any meaningful conclusion between the FTP and MMSS. The MMSS has been considered to represent an exercise intensity that can be sustained without a progressive loss of homeostasis and demarcates the heavy and severe exercise domains (Jones et al., 2019). The threshold between the heavy and severe intensity domains has significant value in sports science as it represents the upper boundary of whether the  $\text{VO}_2$  can remain in a steady state and the ability of the  $\text{VO}_2$  slow component ( $\text{VO}_{2\text{sc}}$ ) to stabilise. The amplitude of the  $\text{VO}_{2\text{sc}}$  is closely related to muscle fatigue development and exercise tolerance (Burnley & Jones, 2007; Colosio et al., 2020). In the heavy domain, the  $\text{VO}_{2\text{sc}}$  can stabilise, whereas when exercising within the severe intensity domain, the  $\text{VO}_2$  has been shown to project upwards, rising to  $\text{VO}_{2\text{max}}$  without a discernible steady state (Hill et al., 2002; Jones et al., 2019; De Lucas et al., 2013; Poole et al., 1988). Traditionally, the MMSS can be determined using MLSS (Billat et al., 2003; Faude et al., 2009) or the CP (Poole et al., 2021),

both requiring individuals to undertake at least three to four short submaximal effort trials to determine the intensity corresponding to the threshold, which is a time consuming and labour-intensive process. Thus, a single 20-minute maximal effort TT for FTP determination (Inglis et al., 2019; Morgan et al., 2019) could efficiently determine the work rate corresponding to MMSS. However, previous studies have reported a low level of agreement between the measured power outputs associated with CP and FTP and should not be used interchangeably (Karsten, 2018; Morgan et al., 2019; Karsten et al., 2021; McGrath et al., 2021). Similarly, Inglis et al. (2019) reported that the power output corresponding to FTP was significantly higher than the MLSS; therefore, not a valid marker of the threshold between heavy and severe intensity domains. In short, previous research suggests that FTP should not be used interchangeably with CP and MLSS or as a marker of the MMSS. Nonetheless, the use of FTP to inform training and design training programmes by coaches and athletes continues to grow (Allen & Coggan, 2010; Borszcz et al., 2018). A possible reason for this is that the little previous research that has been conducted investigating FTP has tended to focus on the statistical perspective (correlation and limits of agreement) with other well-known performance markers rather than the physiological basis of FTP itself (Borszcz et al., 2018; Inglis et al., 2019; Karsten et al., 2021; McGrath et al., 2021). Therefore, to determine the validity of FTP representing the MMSS, there is a need to examine the physiological responses to exercise at and above the FTP and identify whether they correspond to the heavy and severe intensity domain, respectively.

The present study aimed to investigate the validity of FTP being the threshold separating the heavy and severe intensity domains by examining the physiological response when exercising at and 15 W above FTP (FTP<sub>+15W</sub>). Specifically, the study compared the VO<sub>2sc</sub> response between exercising at and above FTP due to its ability to discriminate between heavy and severe

exercise intensity domains (Burnley & Jones, 2007). The null hypothesis of the present study was that there would be no significant difference in VO<sub>2sc</sub>, %VO<sub>2peak</sub> and blood lactate when exercising at FTP and FTP<sub>+15W</sub>.

## Methods

### Participants

Thirteen cyclists (male  $n = 11$ ; Age =  $23.5 \pm 3.9$  years; VO<sub>2peak</sub> =  $60.0 \pm 4.7$  mL·kg<sup>-1</sup>·min<sup>-1</sup>; female  $n = 2$ ; Age =  $26 \pm 9.8$  years; VO<sub>2peak</sub> =  $48.0 \pm 4.0$  mL·kg<sup>-1</sup>·min<sup>-1</sup>) were recruited for this study. Participants were classified into four categories based on their relative and absolute VO<sub>2peak</sub> (De Pauw et al., 2013; see, Table 1). The inclusion criteria were 1) at least three years of cycling experience, 2) a minimum of four hours of training per week, and 3) previous experience with the FTP determination test. Participants were fully informed about the nature of the study, all associated risks, and their right to withdraw at any time before providing written consent. The study was ethically approved by the Human Research Ethics Committee at the Education University of Hong Kong (E2021-2022-0003) in line with the requirements of the declaration of Helsinki.

### Study design

As shown in Figure 1, the study comprised four laboratory visits separated by 24 to 48 hours. During the first visit, participants were required to undertake a ramp incremental exercise test to determine their maximal oxygen uptake (VO<sub>2peak</sub>). Visit 2 was conducted to determine the participant's FTP, which was subsequently used in visits 3 and 4, the main experimental trials. The order of the 3<sup>rd</sup> and 4<sup>th</sup> visits was randomised and required the participant to cycle for 40 minutes or to task failure,

Table 1. Characteristics of the participants.

Participant	Height (cm)	Mass (kg)	Relative VO <sub>2peak</sub> (mL·kg <sup>-1</sup> ·min <sup>-1</sup> )	Absolute VO <sub>2peak</sub> (L·min <sup>-1</sup> )	Performance Level (Relative/Absolute)
1	177	70	64	4.49	T/T
2	177	56	60	3.36	T/RT
3	180	65	61	3.95	T/RT
4	173	63	65	4.07	WT/RT
5	176	68	57	3.89	T/RT
6	170	62	64	3.97	T/RT
7*	164	53	51	2.68	RT/UT
8	174	63	55	3.44	T/RT
9	170	58	62	3.59	T/RT
10*	162	42	45	1.89	UT/UT
11	171	53	50	2.66	R/UT
12	180	63	64	4.04	T/RT
13	177	83	58	4.84	T/T

UT = Untrained; RT = Recreationally Trained; T = Trained; WT = Well Trained; \*Female participant

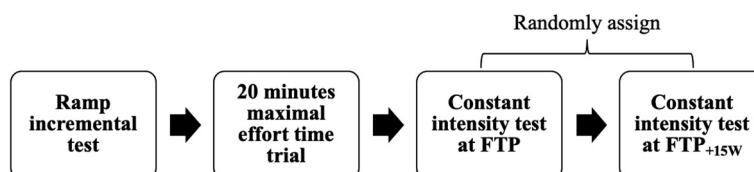


Figure 1. Study design schematic.

whichever occurred first, either at an exercise intensity equivalent to their FTP or FTP<sub>+15W</sub>.

Participants were asked not to engage in strenuous exercise 24 hours before testing and were required to avoid adding new training to their habitual routine during the testing period. They were required to maintain the same diet 24 hours before each test and arrive at the laboratory hydrated without consuming food and caffeine in the preceding three hours. The incremental ramp test and constant intensity tests at FTP and FTP<sub>+15W</sub> were performed on a laboratory cycle ergometer (Lode Excalibur Sport, The Netherlands). The ergometer was calibrated according to the manufacturer's recommendations and adjusted for participant comfort before every use. The FTP determination trial was performed on the participants' bike attached to a stationary bike trainer (Wahoo KICKER v.5; Wahoo Fitness, Atlanta, GA), which was previously shown to possess a high level of accuracy and reliability (Hoon et al., 2016). The pedal frequency was set at the participants' preferred rate between 80 and 90 rpm and held constant throughout the ramp incremental and constant intensity tests ( $\pm 2$  rpm). Pulmonary gas exchange was measured on a breath-by-breath basis using Cortex Metalyzer 3B (Cortex, Leipzig, Germany).

### Incremental ramp test

The incremental ramp test commenced with a warm-up at 50 W for four minutes. The work rate was increased by 30 W.min<sup>-1</sup> for male participants and 25 W.min<sup>-1</sup> for female participants until volitional exhaustion. Breath-by-breath VO<sub>2</sub> data were subsequently averaged in the 30s to determine the VO<sub>2peak</sub> (Nixon et al., 2021).

#### Determination of the FTP

The FTP test started with five minutes of baseline pedalling at 100 W using the preferred cadence, followed by a 20-minute maximal, self-paced TT. The aim of the TT was for the participant to achieve the highest mean power output possible across the 20 minutes with no verbal encouragement from the researcher. Participants were allowed to see the time and cadence to support appropriate pacing (Inglis et al., 2019; Morgan et al., 2019). Indoor cycling training software (Zwift, v1.0.85684, Zwift Inc, US) was used to record PO from all FTP determination trials.

### Constant intensity trials equivalent to FTP and FTP<sub>+15W</sub>

The objective of these visits was to determine the participant's VO<sub>2</sub> and blood lactate responses when exercising at the intensity corresponding to FTP and FTP<sub>+15W</sub>. A change in work rate of  $\pm 15$  W was selected due to previous research that examined similar threshold markers such as CP and MLSS using incremental rates such as 10 W (Maturana et al., 2016; Iannetta et al., 2022) and 5% of VO<sub>2max</sub> (Dekerle et al., 2003), were suggested to be too low to provide conclusive changes in BLC and VO<sub>2</sub> response (Jones et al., 2019). Tests began with a five-minute warm-up at 100 W using the participant's preferred cadence. Participants were then required to cycle at a constant intensity, either equivalent to their FTP or FTP<sub>+15W</sub>, for 40 minutes or until task failure, whichever occurred first. The intensity for the first

trial (FTP or FTP<sub>+15W</sub>) was randomly assigned using a website (<https://www.random.org/lists/>). Task failure was defined as the point at which the participant could no longer maintain a cadence of at least 50 rpm for more than five consecutive seconds despite strong verbal encouragement (Murgatroyd et al., 2011). Blood lactate samples were collected in duplicate from their fingertip before the test (baseline), every 10<sup>th</sup> minutes throughout the test session, and upon task failure (Biosen C-Line, EKF Diagnostics, GmbH, Barleben, Germany).

### Data analysis

The VO<sub>2</sub> data were edited to eliminate the effects of coughs or swallows on the measurement. Only those data points beyond the three standard deviations of the mean value were excluded (Burnley et al., 2006). The first 20s of the VO<sub>2</sub> data following the onset of exercise were removed to eliminate the phase I component from the analysis. The first 2 minutes of the VO<sub>2</sub> data (20 to 120 s) were then analysed using the monoexponential model (Burnley et al., 2005, 2006; Rossiter et al., 2001):

$$\dot{V}O_2(t) = \dot{V}O_{2base} + amp * (1 - e - (t - TD/tau))$$

Where VO<sub>2</sub>(t) = VO<sub>2</sub> at time, VO<sub>2base</sub> = the baseline VO<sub>2</sub> measured in the four minutes before the transition in work rate, amp = amplitude, TD = time delay, and tau = time constant of the primary (phase II) response. The amplitude of the VO<sub>2sc</sub> was determined by the highest VO<sub>2</sub> value achieved during the constant intensity trial and subtracting the "absolute" primary amplitude (VO<sub>2base</sub> + amp; Burnley et al., 2005, 2006). The monoexponential model was chosen because a more complex model will significantly degrade the confidence intervals and create a lot of parameter interdependence (Burnley et al., 2005). Given that the time to task failure (TTF) at FTP and FTP<sub>+15W</sub> varied between participants, the VO<sub>2</sub> data were analysed using the individual isotime method and expressed in relative time (baseline, 25, 50, 75 and 100%) to avoid any data loss (Nicolò et al., 2019). The VO<sub>2</sub> corresponding to the desired time points was determined by the average VO<sub>2</sub> over the prior 60s. The mean of the last two segments (75% and 100%) was considered the VO<sub>2</sub> corresponding to each trial.

Two sets of blood lactate samples were collected before the test, at every 10<sup>th</sup> minute and task failure. The mean of the two blood lactate samples was used for subsequent analysis. The blood lactate kinetic response was interpolated with a linear function using Microsoft Excel (Excel, Microsoft, Redmond, Washington) and represented as BLC<sub>FTP</sub> and BLC<sub>FTP+15W</sub>. The estimated blood lactate concentration (BLC) corresponding to 25, 50, 75 and 100% of the test duration were used to represent the blood lactate kinetics corresponding to FTP (BLC<sub>FTP</sub>) and FTP<sub>+15W</sub> (BLC<sub>FTP+15W</sub>; Nicolò et al., 2019). The actual difference in BLC between the 10<sup>th</sup> minute and end test (BLC <sub>$\Delta$ 10end</sub>) and the actual end test value corresponding to FTP and FTP<sub>+15W</sub> trials were also calculated and subsequently used for statistical analysis purposes.

### Statistical analysis

Prior to analysis, data were checked for normality of distribution using a Shapiro-Wilk test. The VO<sub>2</sub> data were subsequently analysed using two-way ANOVA with repeated measures across



two tests (FTP vs FTP<sub>+15W</sub>) and five time points (Baseline, 25%, 50%, 75% and 100% of the total test duration). The estimated blood lactate kinetics data interpolated with a linear function was analysed using two-way ANOVA with repeated measures across two tests (BLC<sub>FTP</sub> vs BLC<sub>FTP+15W</sub>) and five time points (Baseline, 25%, 50%, 75% and 100% of the total test duration). The significant interaction and main effects were determined using LSD post hoc tests. When sphericity was violated, the F value was adjusted using Greenhouse-Geisser. The end test VO<sub>2</sub>, the BLC<sub>Δ10end</sub> and the end test BLC corresponding to FTP and FTP<sub>+15W</sub> were analysed using paired t-tests. Analyses were performed using IBM SPSS statistics 26.0 (Chicago, IL, USA). Data are reported as mean ± SD unless otherwise stated.

## Results

The mean cycling power output was 222 ± 51 W and 237 ± 51 W at FTP and FTP<sub>+15W</sub>, respectively. Only seven out of thirteen participants were able to sustain exercise at FTP for 40 minutes. The mean TTF at FTP and FTP<sub>+15W</sub> was 33.7 ± 7.6 and 22.0 ± 5.7 min (p < 0.05), respectively. There was a small but significant difference between the end test VO<sub>2</sub> (calculated using the average of 75% and 100% of the total duration) corresponding to FTP and FTP<sub>+15W</sub> (2.97 ± 0.66 vs 3.13 ± 0.67 L·min<sup>-1</sup>, respectively; p < 0.05). The highest VO<sub>2</sub> achieved during both intensities in 10s average was significantly lower than the VO<sub>2peak</sub> measured during the incremental ramp test (VO<sub>2peak</sub>: 3.61 ± 0.81 vs FTP: 3.21 ± 0.69, p < 0.001 and FTP<sub>+15W</sub> 3.33 ± 0.68 L·min<sup>-1</sup>, p < 0.001).

### VO<sub>2</sub> response when exercising at FTP and FTP<sub>+15W</sub>

The VO<sub>2</sub> kinetics analysed using the individual isotime method demonstrated a significant interaction effect between test and time for VO<sub>2</sub> response (F = 2.827, p < 0.05), the main effect of the test (F = 19.015, p < 0.001) and time (F = 85.535, p < 0.001). The VO<sub>2</sub> was significantly different at all time points between the two intensities (p < 0.05), except for baseline. Post hoc analysis showed a significant difference in VO<sub>2</sub> between the baseline and the rest of the time points (p < 0.001) during

both FTP and FTP<sub>+15W</sub>. The VO<sub>2</sub> did not change significantly between 25% of the total duration and the end of the exercise during both FTP and FTP<sub>+15W</sub> (p > 0.05) (see, Figure 2). There was no significant difference in the magnitude of the VO<sub>2sc</sub> when exercising at FTP and FTP<sub>+15W</sub> (399 ± 177 mL·min<sup>-1</sup> vs 409 ± 185 mL·min<sup>-1</sup>, p > 0.05).

### Blood lactate response when exercising at FTP and FTP<sub>+15W</sub>

For the blood lactate kinetics estimated using linear regression, there was a significant interaction between test and time (F = 12.871, p < 0.001), a significant main effect of time (F = 88.110, p < 0.001) and for test (F = 3.12, p = 0.09). Post hoc analysis showed a significant difference between every timepoint for BLC<sub>FTP</sub> and BLC<sub>FTP+15W</sub> (p < 0.05), except for baseline. There was also a significant difference in the BLC from 50% of the test duration to the end test between BLC<sub>FTP</sub> and BLC<sub>FTP+15W</sub> (p < 0.05; see, Figure 3). The estimated BLC<sub>FTP</sub> and BLC<sub>FTP+15W</sub> at each time point were 1.6 ± 0.6, 5.6 ± 2, 6.0 ± 2.0, 6.4 ± 2.0, 6.8 ± 2.1 mM and 1.5 ± 0.5, 6.2 ± 2.0, 7.3 ± 2.2, 8.3 ± 2.5 and 9.3 ± 3.0 mM, respectively. The blood lactate difference between 50% and 100% of the test duration was 0.8 ± 0.7 and 2.0 ± 1.4 mM for FTP and FTP<sub>+15W</sub>, respectively. The actual end test BLC (FTP: 6.7 ± 2.1 vs FTP<sub>+15W</sub>: 9.2 ± 2.9 mM, p < 0.05) and the BLC<sub>Δ10end</sub> between two intensities were significantly different (FTP: 1.1 ± 0.9 vs FTP<sub>+15W</sub>: 2.8 ± 2.3 mM, p < 0.05) between two intensities.

## Discussion

In this study, we examined the physiological response when exercising at and above FTP to determine whether it is a valid representation of the threshold between the heavy and severe intensity domains. The key findings were that i) VO<sub>2peak</sub> was not reached at both intensities; ii) VO<sub>2</sub> stabilised at both intensities; iii) there was no significant difference in the amplitude of the VO<sub>2sc</sub> between two intensities; iv) the actual end test BLC and

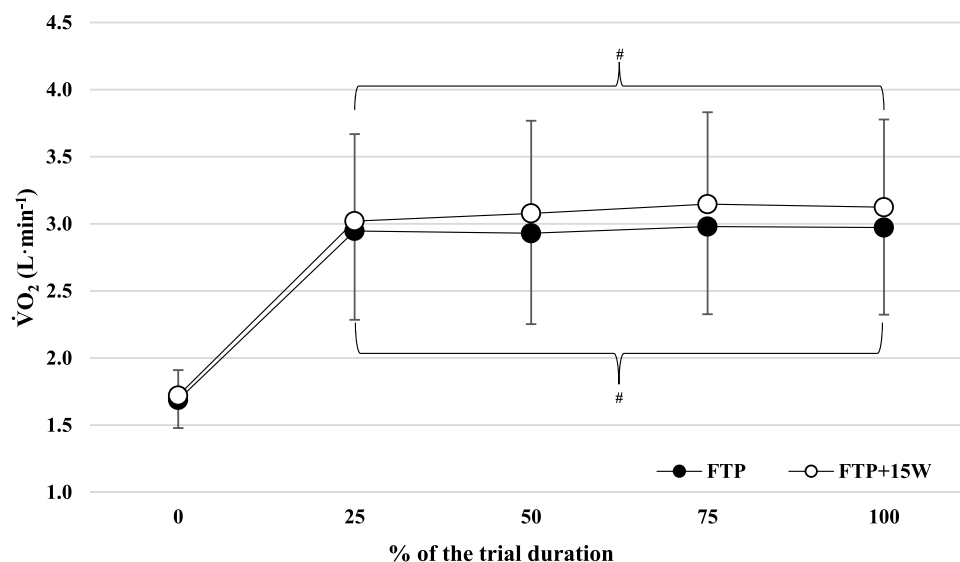
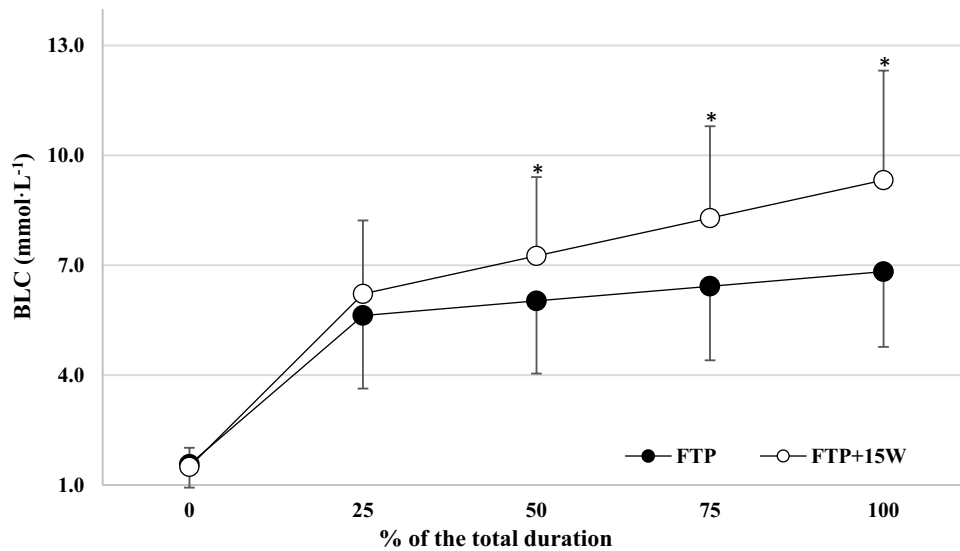


Figure 2. The VO<sub>2</sub> response as a percentage of trial duration when exercising at the intensities corresponding to FTP and FTP<sub>+15W</sub>. #no significant difference (p > 0.05).



**Figure 3.** The blood lactate response as a percentage of trial duration when exercising at intensities corresponding to FTP and FTP<sub>+15W</sub>. \*significantly different from FTP ( $p < 0.05$ ).

the  $BLC_{\Delta 10\text{end}}$  were both significantly higher during FTP<sub>+15W</sub>; v) 46% of the participants reached task failure before 40 minutes when exercising at FTP. Therefore, although the present study did not set out to examine the validity between FTP and hour performance, the results demonstrated that the FTP determined using 95% of a 20-minute TT performance is not a valid estimation of maximal hourly performance. The present study also demonstrated that FTP and FTP<sub>+15W</sub> are within the heavy intensity domain and, therefore, should not be used to represent the physiological threshold between the heavy and severe intensity domains.

### The validity of FTP

The FTP is suggested to represent the maximal power output that a cyclist can sustain for an hour (2010; Allen & Coggan, 2006). Although the original goal of the present study was not to examine the TTF of FTP, the results were in line with previous studies (Borszcz et al., 2018; Sitko et al., 2022). In the present study, only seven out of thirteen participants were able to complete 40 minutes at FTP, the mean TTF for the six participants who reached TTF before 40 minutes was  $26 \pm 4$  minutes demonstrating that FTP is not a valid estimation of the one-hour maximal performance. Contrary to previous research (McGrath et al., 2019) reported that 89% of the participants sustained 60 minutes when exercising at an intensity equivalent to FTP. A possible explanation is that they recruited highly trained subjects therefore with a higher pain/fatigue tolerance ( $VO_{2\text{max}}$ : Male  $66.3 \pm 5.5$  mL·kg·min<sup>-1</sup>; Female  $59.3 \pm 6.9$  mL·kg·min<sup>-1</sup>), whereas the participants in the present study have a lower mean  $VO_{2\text{peak}}$  (Male  $60.0 \pm 4.7$ ; Female  $48.0 \pm 4.0$  mL·kg·min<sup>-1</sup>). However, according to Sitko et al. (2022), even professional cyclists with a  $VO_{2\text{max}}$  of  $74.3 \pm 3.9$  mL·kg·min<sup>-1</sup> and more than 15 years of cycling experience were unable to sustain 60 minutes at the intensity corresponding to the traditionally determined FTP (mean TTF: 51 minutes, ranged from 44 to 59 minutes). Therefore, the FTP should not be

considered a valid representation of what it originally proposed, even when accounting for variables such as cyclists' performance level, experience, and aerobic fitness level (i.e.,  $VO_{2\text{max}}$ ). Although the fatigue development in the heavy intensity domain is complex (Burnley & Jones, 2018), future studies could explore why cyclists reach task failure before the 60 minutes mark when exercising at FTP.

### Oxygen kinetics when exercising at FTP and FTP<sub>+15W</sub>

The threshold between the heavy and severe intensity domain separates whether the  $VO_2$  can remain in a steady state or cannot stabilise and rise towards the  $VO_{2\text{max}}$  (Hill et al., 2002). Therefore, in our view, the question of whether FTP represents the upper boundary of the heavy intensity domain is best assessed by the physiological characteristics, specifically the  $VO_2$  response. In the present study, the  $VO_2$  was not significantly different between 25% of the total duration and the end test when exercising at FTP and FTP<sub>+15W</sub>, indicating a clear  $VO_2$  steady state during both intensities. Contrary to the results reported by Nixon et al. (2021), in which the  $VO_2$  changed significantly between the 5<sup>th</sup> minute and at task failure when exercising slightly above critical speed (CS), the representation of the threshold between the heavy and severe domain in running (Jones et al., 2019). Consistent with our hypothesis, the amplitude of  $VO_{2\text{sc}}$  was not significantly different between the two intensities, indicating that FTP and FTP<sub>+15W</sub> are the same intensity. It has been previously demonstrated that the  $VO_{2\text{sc}}$  is significantly lower during the heavy intensity domain compared to the severe intensity domain (Pringle et al., 2003) because the  $VO_{2\text{sc}}$  cannot be stabilised and rise towards  $VO_{2\text{max}}$  in the severe domain (Burnley & Jones, 2007). Another result from the present study is that FTP should not be considered as the threshold between heavy and severe because the highest  $VO_2$  in 10s average when exercising at FTP and FTP<sub>+15W</sub> was significantly different to  $VO_{2\text{peak}}$ , which means  $VO_2$  was not reached at both intensities. Although the increment rate was

fixed to 15 W in the present study, it was equivalent to a 9% to 12% increase for 3 participants. The percentage of  $\text{VO}_{2\text{peak}}$  corresponding to the  $\text{FTP}_{+15\text{W}}$  remained below 90% for these 3 participants, whereas when exercising within the severe intensity domain until task failure, the  $\text{VO}_2$  should theoretically rise inexorably towards  $\text{VO}_{2\text{max}}$  (De Lucas et al., 2013; Nixon et al., 2021; Poole et al., 1988). Moreover, the results of the present study also suggest that the training intensity zones e.g., > 106% of FTP would train  $\text{VO}_{2\text{max}}$  (2010; Allen & Coggan, 2006) might not be valid because the highest  $\text{VO}_2$  value remains below 90%  $\text{VO}_{2\text{max}}$  when exercising at as high as 112% of FTP. Therefore, based on both the overall  $\text{VO}_2$  kinetics and the inability to attain  $\text{VO}_{2\text{max}}$ , the power output corresponding to  $\text{FTP}_{+15\text{W}}$  does not appear to represent the severe intensity domain. In fact, the intensity corresponding to FTP and  $\text{FTP}_{+15\text{W}}$  may be within the heavy intensity domain (Burnley & Jones, 2007; Hill et al., 2002). Additionally, the intensity corresponding to the FTP is not appropriate to use as a reference for designing training programmes as it has a high chance of overestimating the  $\text{VO}_2$  response (i.e., unable to reach the  $\text{VO}_{2\text{max}}$  even when the intensity corresponding to 112% of FTP was prescribed).

### Lactate kinetics of FTP and $\text{FTP}_{+15\text{W}}$

Allen and Coggan (2012) suggested that the FTP could be used interchangeably with the MLSS. Three studies have examined the validity between MLSS and FTP (Borszcz et al., 2019; Inglis et al., 2019; Lillo-Beviá et al., 2022), and the results of which are in line with Allen & Coggan's suggestion (Allen & Coggan, 2012). However, results of the current study demonstrated that the difference in the actual BLC from the 10<sup>th</sup> to 30<sup>th</sup> minute for those who sustained the FTP intensity for at least 30 minutes was  $1.1 \pm 0.2$  mM ( $n = 9$ ), which exceeds the suggested conventional criterion for the determination of the conventional MLSS (change in BLC < 1.0 mM between the 10<sup>th</sup> and 30<sup>th</sup> minute). Therefore, using the conventional determination criterion for MLSS suggested that the power output corresponding to FTP is not a valid surrogate of MLSS as the  $\text{BLC}_{\text{FTP}}$  was not in a steady state. However, a paper recently published by Nixon et al. (2021) proposed that the criterion for BLC should be 2 mM between 10 to 20 minutes instead of the conventional criterion because the MLSS determined using this protocol eliminated the difference with Critical Speed (CS). When adopting this modified approach, the FTP examined in the present study fulfilled the criterion for being accepted as MLSS ( $0.8 \pm 0.6$  mM) for all thirteen participants. Similarly, Iannetta et al., (2022) also proposed a modified MLSS criterion of using data from the time window of 20 to 30 minutes instead of the conventional method because it has a higher agreement with MMSS. In the present study, for those who cycled for at least 30 minutes when exercising at FTP ( $n = 9$ ), the actual BLC difference between 20 to 30 minutes was  $0.3 \pm 0.6$  mM, which also meets the modified criterion for MLSS proposed by (Iannetta et al., 2022). Therefore, the ability of FTP to provide an approximation of the MLSS appears to be influenced by the criterion used to determine the MLSS. On the other hand, the blood lactate data estimated using the linear function showed a clear dissociation between blood lactate and  $\text{VO}_2$  kinetics. Therefore, it could be argued that relying solely on blood

lactate to provide an indication of a given level of systemic homeostasis and the threshold between heavy and severe intensity domains might be inappropriate as it does not reflect the  $\text{VO}_2$  kinetics. As such, there is a need for scientific validation of the criterion for determining MLSS and blood lactate steady state, and it is premature to conclude whether FTP can be used to represent MLSS.

### Conclusion

The present study demonstrated that FTP should not be considered a marker of the threshold separating the heavy and severe domains for cyclists. Therefore, not a valid representation of the MMSS. The conclusion from the present study is based on the  $\text{VO}_2$  response when exercising at FTP and  $\text{FTP}_{+15\text{W}}$ . There was no significant difference in the  $\text{VO}_{2\text{sc}}$ , and a clear  $\text{VO}_2$  steady state was shown when exercising at both intensities. Most importantly, the  $\text{VO}_2$  did not project towards  $\text{VO}_{2\text{max}}$  when exercising at FTP and  $\text{FTP}_{+15\text{W}}$ . Future studies should examine the value of FTP, other than a valid 20-minute TT indicator, and whether it can be used as an alternative to conventional and modified MLSS.

### Disclosure statement

No potential conflict of interest was reported by the author(s).19912022

### Funding

The author(s) reported there is no funding associated with the work featured in this article.

### ORCID

Stephen Wong  <http://orcid.org/0000-0002-3737-495X>  
 Mark Burnley  <http://orcid.org/0000-0003-3407-561X>  
 Alexis Mauger  <http://orcid.org/0000-0001-6685-5800>  
 Sun Fenghua  <http://orcid.org/0000-0001-5251-4087>  
 James Hopker  <http://orcid.org/0000-0002-4786-7037>

### References

- Allen, H., & Coggan, A. (2006). *Training and racing with a power meter* (1st ed.). Velo Press.
- Allen, H., & Coggan, A. (2010). *Training and racing with a power meter* (2nd ed.). Velo Press.
- Allen, H., & Coggan, A. (2012). *Training and racing with a power meter* (3rd ed.). Velo Press.
- Billat, V. L., Sirvent, P., Py, G., Koralsztein, J. P., & Mercier, J. (2003). The concept of maximal lactate steady state. *Sports Medicine*, 33(6), 407–426. <https://doi.org/10.2165/00007256-200333060-00003>
- Borszcz, F. K., Tramontin, A. F., Bossi, A. H., Carminatti, L. J., & Costa, V. P. (2018). Functional threshold power in cyclists: Validity of the concept and physiological responses. *International Journal of Sports Medicine*, 39(10), 737–742. <https://doi.org/10.1055/s-0044-101546>
- Borszcz, F. K., Tramontin, A. F., & Costa, V. P. (2019). Is the functional threshold power interchangeable with the maximal lactate steady state in trained cyclists? *International Journal of Sports Physiology and Performance*, 14(8), 1029–1035. <https://doi.org/10.1123/ijsp.2018-0572>
- Burnley, M., Doust, J. H., & Jones, A. M. (2005). Effects of prior warm-up regime on severe-intensity cycling performance. *Medicine & Science in Sports & Exercise*, 37(5), 838–845. <https://doi.org/10.1249/01.MSS.0000162617.18250.77>



- Burnley, M., Doust, J. H., & Jones, A. M. (2006). Time required for the restoration of normal heavy exercise VO<sub>2</sub> kinetics following prior heavy exercise. *Journal of Applied Physiology*, 101(5), 1320–1327. <https://doi.org/10.1152/jappphysiol.00475.2006>
- Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science*, 7(2), 63–79. <https://doi.org/10.1080/17461390701456148>
- Burnley, M., & Jones, A. M. (2018). Power–duration relationship: Physiology, fatigue, and the limits of human performance. *European Journal of Sport Science*, 18(1), 1–12. <https://doi.org/10.1080/17461391.2016.1249524>
- Colosio, A. L., Caen, K., Bourgois, J. G., Boone, J., & Pogliaghi, S. (2020). Bioenergetics of the VO<sub>2</sub> slow component between exercise intensity domains. *Pflügers Archiv-European Journal of Physiology*, 472(10), 1447–1456. <https://doi.org/10.1007/s00424-020-02437-7>
- Coyle E F., Feltner M. E., Kautz S. A., Hamilton M. T., Montain S. J., Baylor A. M., Abraham L. D., Petrek G. W. (1991). Physiological and biomechanical factors associated with elite endurance cycling performance. *Med Sci Sports Exerc*, 23(1), 93–107.
- Dekerle J., Baron B., Dupont L., Vanvelcenaher J. & Pelayo P. (2003). Maximal lactate steady state, respiratory compensation threshold and critical power. *Eur J Appl Physiol*, 89(3), 281–288. [10.1007/s00421-002-0786-y](https://doi.org/10.1007/s00421-002-0786-y)
- De Lucas, R. D., De Souza, K. M., Costa, V. P., Grossi, T., & Guglielmo, L. G. A. (2013). Time to exhaustion at and above critical power in trained cyclists: The relationship between heavy and severe intensity domains. *Science & Sports*, 28(1), e9–e14. <https://doi.org/10.1016/j.scispo.2012.04.004>
- De Pauw, K., Roelands B., Cheung S. S., de Geus B., Rietjens G., & Meeusen R. (2013). Guidelines to Classify Subject Groups in Sport-Science Research. *International Journal of Sports Physiology and Performance*, 8(2), 111–122. <https://doi.org/10.1123/ijsspp.8.2.111>
- Dotan R. (2022). A critical review of critical power. *Eur J Appl Physiol*, 122(7), 1559–1588. [10.1007/s00421-022-04922-6](https://doi.org/10.1007/s00421-022-04922-6)
- Faude, O., Kindermann, W., & Meyer, T. (2009). Lactate threshold concepts. *Sports Medicine*, 39(6), 469–490. <https://doi.org/10.2165/00007256-200939060-00003>
- Hill, D. W., Poole, D. C., & Smith, J. C. (2002). The relationship between power and the time to achieve VO<sub>2</sub>max. *Medicine and Science in Sports and Exercise*, 34(4), 709–714. <https://doi.org/10.1097/00005768-200204000-00023>
- Hoon, M. W., Michael, S. W., Patton, R. L., Chapman, P. G., & Areta, J. L. (2016). A comparison of the accuracy and reliability of the Wahoo KICKR and SRM power meter. *Journal of Science and Cycling*, 5(3), 11–15. <https://doi.org/10.28985/jsc.v5i3.240>
- Iannetta D., Inglis E. C., Fullerton C., Passfield L., & Murias J. M. (2018). Metabolic and performance-related consequences of exercising at and slightly above MLSS. *Scand J Med Sci Sports*, 28(12), 2481–2493. [10.1111/sms.13280](https://doi.org/10.1111/sms.13280)
- Iannetta, D., Ingram, C. P., Keir, D. A., & Murias, J. M. (2022). Methodological reconciliation of CP and MLSS and their agreement with the maximal metabolic steady state. *Medicine and Science in Sports and Exercise*, 54(4), 622–632. <https://doi.org/10.1249/mss.0000000000002831>
- Inglis, E. C., Iannetta, D., Passfield, L., & Murias, J. M. (2019). Maximal lactate steady state versus the 20-minute functional threshold power test in well-trained individuals: “Watts” the big deal? *International Journal of Sports Physiology and Performance*, 15(4), 541–547. <https://doi.org/10.1123/ijsspp.2019-0214>
- Jones, A. M., Burnley, M., Black, M. I., Poole, D. C., & Vanhatalo, A. (2019). The maximal metabolic steady state: Redefining the ‘gold standard’. *Physiological Reports*, 7(10), e14098. <https://doi.org/10.1249/MSS.0b013e31821fcf1>
- Karsten, A. (2018). Relation between critical power and functional threshold power. *Journal of Science and Cycling*, 6(3), 41–42. <https://jsc-journal.com/index.php/JSC/article/view/354>
- Karsten, B., Petrigna, L., Klose, A., Bianco, A., Townsend, N., & Triska, C. (2021). Relationship between the critical power test and a 20-min functional threshold power test in cycling. *Frontiers in Physiology*, 1877. <https://doi.org/10.3389/fphys.2020.613151>
- Lillo-Beviá, J. R., Courel-Ibáñez, J., Cerezuela-Espejo, V., Morán-Navarro, R., Martínez-Cava, A., & Pallarés, J. G. (2022). Is the functional threshold power a valid metric to estimate the maximal lactate steady state in cyclists? *Journal of Strength and Conditioning Research*, 36(1), 167–173. <https://doi.org/10.1519/JSC.0000000000003403>
- Mattioni Maturana F., Keir D. A., McLay K. M. and Murias J. M. (2016). Can measures of critical power precisely estimate the maximal metabolic steady-state?. *Appl. Physiol. Nutr. Metab.*, 41(11), 1197–1203. [10.1139/apnm-2016-0248](https://doi.org/10.1139/apnm-2016-0248)
- McGrath, E., Mahony, N., Fleming, N., & Donne, B. (2019). Is the FTP test a reliable, reproducible and functional assessment tool in highly-trained athletes? *International Journal of Exercise Science*, 12(4), 1334–1345 <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6886609/> .
- McGrath, E., Mahony, N., Fleming, N., Raleigh, C., & Donne, B. (2021). Do critical and functional threshold powers equate in highly-trained athletes? *International Journal of Exercise Science*, 14(4), 45–59 <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8136559/> .
- Morgan, P. T., Black, M. I., Bailey, S. J., Jones, A. M., & Vanhatalo, A. (2019). Road cycle TT performance: Relationship to the power-duration model and association with FTP. *Journal of Sports Sciences*, 37(8), 902–910. <https://doi.org/10.1080/02640414.2018.1535772>
- Murgatroyd, S. R., Ferguson, C., Ward, S. A., Whipp, B. J., & Rossiter, H. B. (2011). Pulmonary O<sub>2</sub> uptake kinetics as a determinant of high-intensity exercise tolerance in humans. *Journal of Applied Physiology*, 110(6), 1598–1606. <https://doi.org/10.1080/02640414.2018.1535772>
- Nicolò, A., Sacchetti, M., Girardi, M., McCormick, A., Angius, L., Bazzucchi, I., & Marcora, S. M. (2019). A comparison of different methods to analyse data collected during time-to-exhaustion tests. *Sport Sciences for Health*, 15(3), 667–679. <https://doi.org/10.1007/s11332-019-00585-7>
- Nixon, R. J., Kranen, S. H., Vanhatalo, A., & Jones, A. M. (2021). Steady-state VO<sub>2</sub> above MLSS: Evidence that critical speed better represents maximal metabolic steady state in well-trained runners. *European Journal of Applied Physiology*, 121(11), 3133–3144. <https://doi.org/10.1007/s00421-021-04780-8>
- Poole, D. C., Rossiter, H. B., Brooks, G. A., & Gladden, L. B. (2021). The anaerobic threshold: 50+ years of controversy. *The Journal of Physiology*, 599(3), 737–767. <https://doi.org/10.1113/JP280980>
- Poole, D. C., Ward, S. A., Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, 31(9), 1265–1279. <https://doi.org/10.1080/00140138808966766>
- Pringle, J. S., Doust, J. H., Carter, H., Tolfrey, K., Campbell, I. T., & Jones, A. M. (2003). Oxygen uptake kinetics during moderate, heavy and severe intensity ‘submaximal’ exercise in humans: The influence of muscle fibre type and capillarisation. *European Journal of Applied Physiology*, 89(3), 289–300. <https://doi.org/10.1007/s00421-003-0799-1>
- Rossiter, H. B., Ward, S. A., Kowalchuk, J. M., Howe, F. A., Griffiths, J. R., & Whipp, B. J. (2001). Effects of prior exercise on oxygen uptake and phosphocreatine kinetics during high-intensity knee-extension exercise in humans. *The Journal of Physiology*, 537(1), 291–303. <https://doi.org/10.1111/j.1469-7793.2001.0291k.x>
- Sitko, S., Cirer-Sastre, R., & López-Laval, I. (2022). Time to exhaustion at estimated functional threshold power in road cyclists of different performance levels. *Journal of Science and Medicine in Sport*, 25(9), 783–786. <https://doi.org/10.1016/j.jsams.2022.06.007>