NORWEGIAN SCHOOL
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# Understanding the workload demands of Cross-country mountain bike cycling using the Critical Power concept

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# Abstract

**Objective:** To examine the pacing pattern by describing the continuous workload requirements in relation to critical power (CP) of cross-country mountain bike cycling (XCO-MTB).

**Methods:** Five male and two female nationally competitive XCO-MTB athletes (age:23± 4 years, $VO_{2peak}$:71 ± 8.1 mL·kg$^{-1}$·min$^{-1}$) completed an official XCO-MTB race and then performed two lab tests using their own bike mounted on a cycle ergometer with their own power meter. Speed, cadence, power output, and HR were recorded during the XCO-MTB race. $VO_{2peak}$ and maximal aerobic power (MAP) were established, and CP were calculated using three maximum effort time trials of 12, 7 and 3 minutes. PO >CP were divided into three magnitude based zones [P] (CP up to 1.5 times CP[P1], 1.5 to 2 times CP[P2]  and 2 times and above CP[P3]), and five zones based on the duration of individual segments with >CP PO.

**Results:** During the XCO-MTB event, average speed and PO was 14.4±1.9km*h$^{-1}$ and 249±63 W, respectively. Average CP was 329±74W and PO varied from 0 to 277±29% of MAP. During the race, 40±8% of race time was spent with PO >CP with mean PO equal to 76±9% of CP. Average percent of lap time spent in P1, P2 and P3 was 25±4 %, 11±6 % and 4±5 %, respectively. Total time >CP and distribution of P2-3 decreased significantly from initial rounds, with no significant changes in P1 or distribution of duration.

**Conclusions:** During this XCO-MTB race, about 40% of race time was spent above the CP, with a reduction of high magnitude >CP actions in P2 and P3 following initial rounds. The observed highly variable pacing pattern in XCO-MTB imply the needs for rapid changes in metabolic power output during races, displaying a prominent number of separate short-lived actions with little lap-to-lap variation in duration.

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On this period. While writing is chiefly done by one's lonesome, the feeling of working together with classmates certainly makes it feel less so. I believe a great deal of the wonder for science is lost when there is an absence of community and scientific discussion. This predicament, or crisis, made writing largely a solitary pursuit, making it more difficult to ask questions, seek assistance or partake in academic discussion. Exacerbated, I think, by my own stubbornness to determinedly seek the things mentioned above. Yet, it seems like there have been more than enough solitude to go around.

*Steffan Næss*

Lier, June 2020

# 1 Table of Contents

# Acronyms

CP – Critical Power

>CP – Above Critical power

<CP – Below Critical power

P1 – Power output from Critical power up to 1.5 times Critical Power

P2 – Power output from 1.5 to 2 times critical power

P3 – Power output above 2 times critical power

TS1 – 1 – 5 consecutive seconds above critical power

TS2 – 6-10 consecutive seconds above critical power

TS3 – 11 to 15 consecutive seconds above critical power

TS4 – 16 to 20 consecutive seconds above critical power

TS5 – above 21 consecutive seconds above critical power

SL – Start loop

R1 – Round 1

R2 – Round 2

R3 – Round 3

Ln-1 – The second to last lap

LN – Last lap

PO – Power Output in watts

MAP – Maximal aerobic output

XCO-MTB – Cross-country mountain biking

$P_{obla}$ – Power output corresponding to the onset of blood lactate accumulation

OBLA – Onset of blood lactate accumulation

PPO – Singular peak power output reading

TT – Time trial

CWR – Constant work rate

RER – Respiratory exchange rate

$VO_2$ – Ventilatory oxygen uptake

RCP – Respiratory Compensation Point

## 1.1 Introduction

Olympic cross-country mountain biking [XCO-MTB] are off-road cycling events demanding continual high intensity  (Hays, Devys, Bertin, Marquet, & Brisswalter, 2018; Impellizzeri, Rampinini, Sassi, Mognoni, & Marcora, 2005b) and the use of numerous bursts of high power output [PO] (Granier et al., 2018; Inoue, Sa Filho, Mello, & Santos, 2012; Macdermid & Stannard, 2012). The XCO-MTB formats demanding mass-start and varied off-road track structure create a high workload variability, challenging contestant's ability to optimally distribute PO across a race (Impellizzeri, Sassi, Rodriguez-Alonso, Mognoni, & Marcora, 2002; Novak, Bennett, Fransen, & Dascombe, 2018). These challenges have resulted in multiple physiological characteristics being highlighted when attempting to explain what affects performance in the sport (Hays et al., 2018; Impellizzeri, Marcora, Rampinini, Mognoni, & Sassi, 2005a; Macdermid & Stannard, 2012).

Several studies have assessed the determinants of performance in XCO-MTB, demonstrating  convincing evidence for the importance of aerobic characteristics for performance, i.e. $VO_{2max}$ (Hays et al., 2018; Impellizzeri & Marcora, 2007), maximal aerobic power output [MAP] (Granier et al., 2018; Hays et al., 2018),  ventilatory- and lactate thresholds (Impellizzeri et al., 2005a; Miller, Moir, & Stannard, 2014; Viana, Pires, Inoue, & Santos, 2018). Following Inoue et al. (2012) findings suggesting anaerobic power as an important determinant of performance, the high intra-lap variation in workload have been a prominent topic of investigation. Hays et al. (2018) compared the intermittent workload observed in XCO-MTB to that of intermittent team sports, reporting a considerable portion of work performed beyond MAP distributed on a substantial amount of actions.  Furthermore, continuous $VO_2$ measures throughout simulated competition have exhibited a high general intensity than derived from crank based PO, particularly following climbs and beginning of descents (Hays et al., 2018; Macdermid & Morton, 2012). Taken together, the intermittent nature of XCO-MTB races certainly requires a well-developed aerobic capacity to sustain the high intensity, with significant utilization of anaerobic power during crucial moments of the sport.

The fast start followed by even pacing have become a staple in recent description of pacing in XCO-MTB (Abbiss et al., 2013; Granier et al., 2018; Viana et al., 2018). Macdermid and Stannard (2012) have presented position in the starting grid to be an important denominator for finishing position.  Indeed, international competition position riders further towards the front based on UNI (Union Cycliste Internationale) World ranking, which potentially accentuate performance of the high ranking athletes, but also incentivise the aggressive opening to secure a better position in the field (Granier et al., 2018; Macdermid & Morton, 2012; Viana et al., 2018).

While overarching lap-to-lap pacing and unidimensional performance prediction have been successfully applied to XCO-MTB, the extensive intralap variability is not well accounted for (Gregory, Johns, & Walls, 2007; Impellizzeri et al., 2005b; Inoue et al., 2012; Novak et al., 2018). Besides, many of the laboratory tests are not readily available to coaches and athletes due to the need for advanced equipment and training. Miller et al. (2014) presented better prediction utilizing an intermittent test to predict performance, rather than a linear model. Following this path of enquiry, Miller and Macdermid (2015) later proposed Critical power [CP] to be an ecological framework to assess performance in XCO-MTB.

Critical power is considered to be the boundary between steady state and non-steady state exercise, separating the theoretically “infinite” work able to be performed below CP and predictable work available above CP(Jones, Wilkerson, DiMenna, Fulford, & Poole, 2008). In intermittent exercise such as XCO-MTB, workload >CP is believed to steadily drain the finite capacity to perform work above CP (labelled W’), and has been demonstrated to include varying degrees of regeneration of W’ dependent on workload during <CP segments (Chidnok et al., 2012; Chidnok et al., 2013b; Skiba, Chidnok, Vanhatalo, & Jones, 2012). Interestingly, recent studies on the pacing of XCO-MTB have displayed a shift in contribution of above MAP actions, suggesting anaerobic actions to develop throughout an event (Granier et al., 2018; Hays et al., 2018). Due to CPs sensitivity determine work in both aerobic and anaerobic domains, assessing XCO-MTB race through the use this framework could elucidate how anaerobic capacity is utilized throughout a race (Chidnok et al., 2012).

### *1.1.1 Aim*

To the best of our knowledge, no studies have applied the CP concept to examine PO in an XCO-MTB race. Consequently, the aim of this study was to (1) to assess the workload requirements of XCO-MTB using power output and the critical power concept, (2) to examine characteristics of >CP actions throughout a race. We hypothesized that average power output is close to the critical power threshold, and that intensity of actions above critical power to decrease as a function of race time.

# 2 Theory

## 2.1 The Critical Power Model

### 2.1.1 The hyperbolic function of exercise intensity and time

The theory of a hyperbolic function of exercise intensity and time were introduced by Hill in 1927, initiating the research of a relationship of speed over time as were present in World records for both swimming and running. This were later expanded upon by Monod and Scherrer (2007), who are credited with the formal development mathematical framework for the power-duration relationship; the Critical Power model.

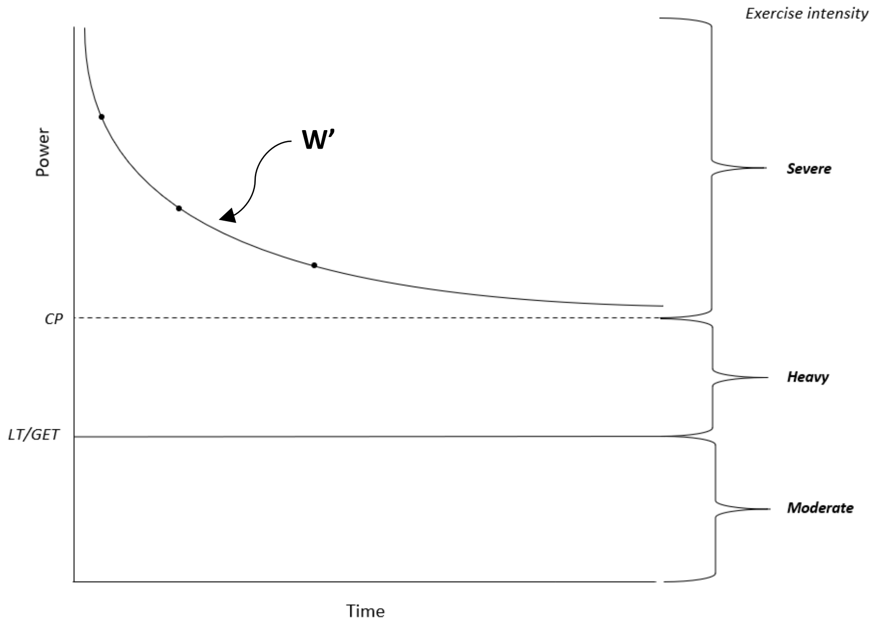



***Figure 2-1** Hyperbolic relationship between power output (y-axis) and time (x-axis), where the critical power is indicated by the power-asymptote and the W' is the curvature constant. Adopted from Poole et al. (2016).*

Fatigue development during exercise is multifaceted in nature and is undoubtedly dictated by intensity and duration, consequently, there is great interest in understanding the determinants of intensity in exercise (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016). The CP concept is generally thought to describe the boundary separating exercise intensity where fatigue does not occur and intensity where we quite comfortably can predict when it does (Poole et al., 2016). Originally, CP was defined as the highest sustainable intensity where exercise could theoretically continue "indefinitely", though "for an extended time without fatigue" was suggested to be better suited in practice (Monod & Scherrer, 2007). Increasing exercise intensity beyond the CP unavoidably taps into a finite work tolerance known as W', described by the curvature constant when plotting power and time (*FIGURE 2-1*). Using these parameters, CP and W', time to termination of exercise *(T)* >CP can be closely estimated using the following equation:

$$T = W'/(P-CP) \qquad [1]$$

This postulates that the limit of exercise >CP is determined by the size of W' and the proportion of power output(P) in relation to the CP threshold (Poole et al., 2016). The magnitude of P directly alters the rate of W' expenditure, which in turn, determines *T*. The interactions above require the assumption that T is purely a result of the values of CP (in W) and W' (In J), and that the parameters remain fixed over the duration of exercise with termination of exercise when W' is exhausted, as described by Hill (1993). However, it is evident that the parameters are not impervious to variations during exercise, for example through changes in cadence (Barker, Poole, Noble, & Barstow, 2006), duration (Jones et al., 2008) and pacing (Vanhatalo, Jones, & Burnley, 2011). Therefore, when applying the CP model, we must acknowledge that the mathematical formulation assumes some unrealistic scenarios at its extremes e.g. infinite duration at/or below CP or instantaneous expenditure of the entire W' capacity (Morton, 2006).

Despite providing a simplified view of exercise dynamics, CP have demonstrated to describe a remarkably robust relationship between power and duration (Morton, 2006). While the most obvious application the concept is through continuous whole-body exercise such as running (Florence & Weir, 1997), rowing (Morton, 2006), swimming (Nikitakis, Paradisis, Bogdanis, & Toubekis, 2019; Toubekis & Tokmakidis, 2013) and cycling (Chidnok et al., 2012; Karsten, Jobson, Hopker, Stevens, & Beedie, 2015), the concept have proven to be applicable to intermittent sports like rugby (Clarke, Presland, Rattray, & Pyne, 2014), soccer (Clark, West, Reynolds, Murray, & Pettitt, 2013), table tennis (Zagatto, Papoti, & Gobatto, 2008), cross-country skiing (Gloersen, Gilgien, Dysthe, Malthe-Sorenssen, & Losnegard, 2020), as well as intermittent cycling (Chidnok et al., 2012). Substituting power for velocity, force etc. where suitable (Poole et al., 2016). Nevertheless, the consistent reliability and validity across different methods of estimation, even with the reported limitations, supports the use of CP as a tool for describing exercise intensity (Nimmerichter, Prinz, Gumpenberger, Heider, & Wirth, 2020; Pettitt, 2016; Triska et al., 2017)

### *2.1.2 Determination of Critical Power*

Traditionally, the determination of CP and W' have been based on 3-5 separate constant work rate [CWR] time to exhaustion trials, ranging from 2-15 minutes (Muniz-Pumares, Karsten, Triska, & Glaister, 2019). As this method usually requires at least 24 hours between each test, several attempts have been made to simplify the protocol and establish a less time-consuming method. The wide-spread use of ergometers and portable power meters have facilitated new methods to cater to athletes and coaches, leading to multiple different methods for determining CP (Muniz-Pumares et al., 2019).

#### *2.1.2.1 Conventional determination*

The conventional method to determine CP and W' is from 3-5 exhaustive trials ranging from 2-15 minutes, employing different speed (Pettitt, 2016), PO (Poole et al., 2016) or more recently, time (Karsten et al., 2015). It is paramount that participants produce maximum effort for all trials (Jones, Burnley, Black, Poole, & Vanhatalo, 2019). There are different methodological factors which can affect the determination of CP, the main ones being cadence (Hill, 1993), duration (Bishop & Jenkins, 1995; Jenkins, Kretek, & Bishop, 1998; Maturana, Keir, McLay, & Murias, 2017; Triska et al., 2017), number of trials (Muniz-Pumares et al., 2019) and duration of recovery between trials (Karsten et al., 2017; Triska et al., 2018).

The methodology used in this study were first proposed by Karsten *et al.* (2015), demonstrating high reliability for CP using field based time trials[TT]. However, the reliability of the W' parameter could not be established. Karsten et al. (2017) later expanded upon the applicability of TT for establishing the power-time relationship, investigating different inter-trial recovery times in an attempt to reduce the time required for CP testing, with 24h, 3h and 30 min recovery. Intriguingly, the calculated CP still displayed a low prediction error with both 3h and 30 min protocols, supporting the use of ecological TT testing for determination of CP. On the other hand, W' maintained an unacceptably large variation in the measurement (Karsten et al., 2017). To assess the reliability of TT in a laboratory setting, Triska et al. (2017) proposed that familiarization could potentially increase the reliability of TT testing, suggesting a potential learning effect in TT which would increase precision of the model after multiple tests. Even though the first day of testing provided reliable estimations of CP, subsequent tests increased the quality of the model; demonstrating familiarization to be highly recommended when determining CP (Triska et al., 2017).

#### *2.1.2.2 3-minute all out*

A recent contribution to CP methodology is the 3-minute all out test, deemed valid and reliable (Broxterman, Ade, Poole, Harms, & Barstow, 2013; Burnley & Jones, 2007; Muniz-Pumares et al., 2019). The main objective of this test was to forego the multi-day testing protocol. Instead, employing one all-out test to establish CP and W', however, the original protocol still required two days for testing as cadence, $VO_{2max}$, and gas exchange threshold was needed for preparing ergometer settings (Burnley & Jones, 2007; Vanhatalo, Doust, & Burnley, 2007). The test requires sustained maximal effort over three minutes, where W' usually are exhausted by ~2 minutes with the last 30 seconds of the test signifying the equivalent of CP(EP), and all work above CP is the equivalent of W'(WEP) (Vanhatalo et al., 2007).

Muniz-Pumares et al. (2019) have presented guidelines for a valid 3-minute all out test:

1. Somewhat stabilized PO for the last 30 seconds of the test, signifying EP
2. Early attainment of peak PO, preferably within 10 seconds, to prevent pacing
3. Rapid decline in PO following peak PO attainment, depleting "W'" during the first half of the test
4. No decrease of EP by 5% or more for 5 seconds or more during the entire test
5. Maintaining previously determined cadence throughout the test, ending within 10 rpm
6. Reaching $VO_{2max}$
7. Blood lactate concentration >7 $mmol*L^{-1}$

Both parameters have displayed a similar variation and reliability to the conventional testing approach , with CP displaying a higher reliability than W' (Muniz-Pumares et al., 2019).

### *2.1.3 CP*

Advancing the original definition of a theoretical infinite exercise duration at or below CP, it is now considered the highest sustainable rate of oxidative metabolism without a continuous loss of homeostasis (Jones et al., 2008; Poole et al., 2016; Poole, Ward, Gardner, & Whipp, 1988).

To elucidate the specific physiological characteristics surrounding performance around this definition of CP, Jones et al. (2008) tested single-leg knee extension exercise to exhaustion at 10% above and below CP. Initiation of the <CP workload exhibited a rapid decrease in phosphocreatine [PCr] along with transient changes in inorganic phosphate[$P_i$] concentrations and muscle pH, however, all variables stabilized within 3 minutes and all participants completed the 20 min test without much trouble. Conversely, the >CP workload saw a progressive change in the variables until termination of exercise in 14.7 ± 7.1 min, leading to the conclusion that CP is the highest steady-state exercise intensity which does not elicit a progressive degeneration of homeostasis (Jones et al., 2008). This builds upon the early investigations of Poole et al. (1988), describing exercise intensity at a threshold associated with CP to reach steady state, but a significant decrease in exercise tolerance at an intensity equating to 5% above CP. Furthermore, they suggest the metabolic disturbance to be a large contributor to the continual increase of $VO_2$ observed at a >CP PO (Poole., 1988). Later studies have elaborated on the work of Poole et al. (1988) and Jones et al. (2008), investigating CP role as an indicator of exercise intensity domains through distinct responses, assigning CP as the threshold between "Heavy" and "Severe" exercise intensity (Black et al., 2017; De Lucas, De Souza, Costa, Grossl, & Guglielmo, 2013). Essentially, "Severe" exercise intensity is associated with a relentless increase in $VO_2$ and blood lactate until maximal values are reached or exhaustion occur in parallel with depletion of W' (Poole et al., 1988).

Furthering the applicability of the CP threshold is the consistency with established physiological intensity markers, namely the lactate/gas exchange threshold and maximal oxygen uptake [$VO_{2max}$] testing (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010). Moreover, multiple studies have noted an overlap with maximal lactate steady state[MLSS], which represents an equilibrium of lactate production and elimination (Pallares, Moran-Navarro, Ortega, Fernandez-Elias, & Mora-Rodriguez, 2016). Though, the parameters are not to be used interchangeably, as CP are reported to be located at a higher intensity (Dekerle, Baron, Dupont, Vanvelcenaher, & Pelayo, 2003; Miller & Macdermid, 2015).

In conclusion, CP describe a steady-state intensity without significant metabolic disruptions or gradual loss of homeostasis (Poole et al., 2016). Intensity above a known CP will inevitably accumulate fatigue through distinct processes and allow a predictable time to exhaustion (Jones et al., 2019; Poole et al., 2016).

### *2.1.4 W'*

Originally regarded as anaerobic work capacity, the inner workings of W' remains surprisingly elusive given the degree of certainty CP are established as the intensity without a continuous reduction in W' (Poole et al., 2016). Essentially, the W' parameter is generally believed to define the finite work available above CP measured in Joules, although the physiological underpinnings of this capacity remains a topic of debate (Jones et al., 2010; Muniz-Pumares et al., 2019; Skiba, Fulford, Clarke, Vanhatalo, & Jones, 2015)

Although the factors affecting W' are complex, several different interventions have elicited a response in W'. Interestingly, W' have displayed impaired function during interventions which have positively affected CP, e.g. in response to hyperoxia (Vanhatalo, Fulford, DiMenna, & Jones, 2010) and endurance training (Vanhatalo & Jones, 2009). Conversely, high intensity training and the availability of high-intensity substrate appears to affect W' to a greater degree (Miura, Sato, Sato, Whipp, & Fukuba, 2000; Vanhatalo & Jones, 2009). Moreover, reducing the availability of oxygen did not significantly change W' response to exercise, in contrast to CP (Dekerle, Mucci, & Carter, 2012; Townsend, Nichols, Skiba, Racinais, & Periard, 2017). Poole et al. (2016) suggests that raising the threshold for severe intensity adversely affect W', however, the mechanics are not immediately apparent but suggests an integrated relationship between CP and W' (Vanhatalo et al., 2010).

Multiple studies have calculated the depletion and recovery during intermittent work, assuming the rate of W' expenditure remains linear and doesn't fluctuate during exercise (Chidnok et al., 2013b; Ferguson et al., 2010; Skiba et al., 2012; Skiba et al., 2015; Skiba, Jackman, Clarke, Vanhatalo, & Jones, 2014). The ability to accurately predict variations in the state of W' suggest a predictable process, allowing for correlations to physiological characteristics which could lead to a better understanding off the underlying mechanisms (Skiba et al., 2015). Ferguson et al. (2010) suggested accumulation of key fatigue metabolites might clarify the mechanisms surrounding recovery of W', this supports earlier studies on CP as the threshold for "Severe" exercise intensity (Black et al., 2017; De Lucas et al., 2013; Jones et al., 2008; Poole et al., 1988).

Ultimately, it is likely that the W' reflect multiple different variables which dynamically determine the tolerable exercise duration, the precise foundations still remain vague (Poole et al., 2016).

### 2.1.5 Factors affecting the Critical Power model

#### 2.1.5.1 Mathematical modelling

Before assessing what affects the physiological basis of the CP concept, it is important to consider the possible effects of mathematical model used on the resultant CP and W' (Muniz-Pumares et al., 2019). Multiple studies have demonstrated an inherent inaccuracy in calculation of the parameters, resulting in a large range (20-60 min) of reported time to exhaustion at CP (Bull, Housh, Johnson, & Rana, 2008; Hill, 1993; Nimmerichter, Novak, Triska, Prinz, & Breese, 2017; Triska et al., 2018). While the estimations of CP result in a singular Watt value, one should consider CP to encompass ± 5 % of calculated value since time to exhaustion and CP display some inherent biological variability (Jones et al., 2019; Poole et al., 1988).

The choice of mathematical modelling is still not firmly established; therefore, its recommended to employ the model which results in the lowest error, deemed satisfactory if it has a standard error less than 5% for CP and 10% for W' (Hill, 1993; Muniz-Pumares et al., 2019). While the estimations from different models typically favour either CP or W', slight changes in $T_{lim}$ have displayed disproportionate changes in W' compared to CP (Muniz-Pumares et al., 2019).

#### 2.1.5.2 $VO_2$ slow component

For exercise intensity above the gas exchange threshold and CP, $VO_2$ slow component appears as a major determinator of subsequent activity. It is signified by a continued rise of $VO_2$ past the temporary overshoot of constant load exercise, which either results in delayed attainment of steady state or an inexorable rise of $VO_2$ (Jones et al., 2019; Poole et al., 1988; Pringle et al., 2003). Steady state will eventually be attained if exercise intensity remains below the upper domain of MLSS i.e. the heavy intensity domain (Poole et al., 2016; Pringle et al., 2003). Exercise with severe intensity will ultimately reach $VO_{2max}$ or termination of exercise, as 02 cost of movement at any given work rate increases as a function of time which progressively increases drain on W' (Krustrup, Soderlund, Mohr, & Bangsbo, 2004; Vanhatalo et al., 2010). This is believed to be a result of gradual loss of efficiency within activated muscle (Haseler, Kindig, Richardson, & Hogan, 2004; Poole et al., 1988; Rossiter et al., 2002; Vanhatalo et al., 2010) and disproportionate increased recruitment of type II fibres (Barstow, Jones, Nguyen, & Casaburi, 1996; Krustrup et al., 2004; Pringle et al., 2003). Nevertheless, it is evident that $VO_2$ slow component and the accompanying metabolite disturbance and increased cost of movement are important in determining rate of W' depletion, it has also been noted that depletion of W' and attainment of $VO_{2max}$ coincide (Burnley & Jones, 2007; Pringle et al., 2003; Vanhatalo et al., 2010).

#### *2.1.5.3 Maximal oxygen uptake*

The $VO_{2max}$ has been defined as the peak rate of oxygen turnover attainable, as any further increase in exercise intensity will not result in increased $VO_2$ (Ferretti, 2014). The underlying theories for a cardiovascular limit of $VO_2$ are layered, though oxygen transport, systemic- or muscle oxygen delivery are generally thought to be the main regulators of $VO_2$ surrounding maximal exercise (Ferretti, 2014). The extent of drain on W' is governed by the difference between CP and $VO_{2max}$, consequently, alterations in $VO_{2max}$ may result in changes in the CP model (Poole et al., 2016).

Burnley and Jones (2007) have proposed the mechanics surrounding W' to be fourfold, presenting the available work above CP to be a function of the $VO_2$ slow component and the accompanying accumulation of metabolites, depletion of intramuscular substrates and the $VO_{2max}$. Evidently, altering parameters in relation to $VO_{2max}$ affected CP and W' in different degrees, displaying increased effectiveness aerobic parameters in response to factors affecting positively oxygen utilization (Jenkins & Quigley, 1992; Vanhatalo et al., 2010), with adverse effects in hypoxic conditions (Dekerle et al., 2012; Townsend et al., 2017).

#### *2.1.5.4 Pacing strategy*

Variations in strategies leading up to and during exercise have displayed impact on performance during high intensity exercise. Bailey, Wilkerson, Dimenna, and Jones (2009) have reported significantly accelerated $VO_2$ kinetics for severe intensity exercise following a combination of sufficiently intense exercise and recovery prior exercise start. Indeed, an increased rate of rise of $VO_2$ have exhibited an increase in performance, which is evident in pacing strategies which employ a fast start (Abbiss & Laursen, 2008; Burnley & Jones, 2007; de Koning, Bobbert, & Foster, 1999). However, the effects of this diminishes for longer exercise duration as exercise intensity and relative anaerobic contribution decrease, though should not be excluded as a potential factor (Tucker & Noakes, 2009).

### 2.1.6 Application to intermittent exercise

The effects of variable workloads fluctuating above and below the CP threshold might impact the mechanics surrounding rate of depletion for the W’ parameter. As mentioned earlier, a variable workload is reported to include reconstitution of W’ provided recovery intensity is below severe (Jones & Vanhatalo, 2017). Understanding the magnitude of depletion and recovery aspects of W’ could allow for a more accurate understanding of the physiological workload in intermittent sports.

#### 2.1.6.1 Understanding W’ in intermittent exercise

Morton and Billat (2004) provided an early concept for the recovery of work capacity during intermittent exercise using four independent variables to determine extent of recovery. The model considered: Power output during work interval [$P_w$], power output during rest [$P_r$], duration of work interval [$T_w$] and duration of rest interval [$T_r$] with the following assumptions (Morton & Billat, 2004):

1. Average PO must exceed CP during work intervals
2. Average PO during rest must be below CP
3. Average PO over the whole exercise must exceed CP

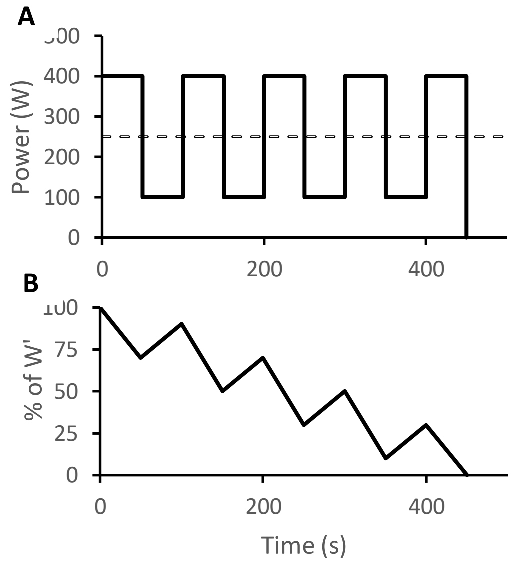



*__Figure 2-2__ Theoretical time course for intermittent work A) power output until exhaustion, stippled line representing CP t=450 s B) W’ during work and rest periods until exhaustion from the above workload. Adapted from Morton et al. (2003)*

If these preconditions are met, a time until exhaustion could resemble figure 2-2 with a small amount of W’ being recovered when PO is below CP. Logically, tweaking any of the accompanying variables will in this theory lead to either increase or decrease in performance time, principally through manipulation of recovery of W’ (Jones & Vanhatalo, 2017; Morton & Billat, 2004). For example, a decrease in $P_r$, $T_w$ or $P_w$ will all result in greater reconstitution of W’. An inherent assumption of this model is the linear reconstitution of W’, which have later been demonstrated to be an oversimplification of recovery dynamics (Bartram, Thewlis, Martin, & Norton, 2018; Chidnok et al., 2013a; Skiba et al., 2014).

To better understand intensities surrounding CP, Coats et al. (2003) tested the hypothesis that following exhaustion intensity need to be reduced to below CP to continue. Six participants completed a CWR to exhaustion before abruptly switching intensity to 80, 90, or 110 % of CP, and instructed to maintain intensity for 20 minutes. Expectedly, no participants completed 110% of CP. However, while all six of the participants completed the 80 % workload, only two managed to sustain all 20 minutes in the 90 % workload (Coats et al., 2003). This supports the intermittent W' recovery model, where W' is sensitive to intensity following exhaustion and should factor into calculations when estimating recovery.

Building on this theory of recovery, Ferguson et al. (2010) later set out to examine reconstitution of W' in relation to $VO_2$ and lactate clearance after an exhaustive exercise bout. Following a supra-CP test predicted to result in exhaustion in six minutes, participants completed a 20 W resting phase lasting 2, 6 or 15 minutes, followed by a constant load test until exhaustion. The hyperbolic power-duration relationship remained robust during all tests, with no notable changes in CP. Reconstitution of W' were significantly changed as a consequence of previous exercise and insufficient rest, displaying a curvilinear recovery pattern. Compared to the control condition with no previous exercise, W' expended was 13.8 kJ, 7.5 kJ and 3.1 kJ lower for 2, 6 and 15 min in that order. The authors suggested a significant effect of time on W' recovery, with the effectiveness of reconstitution diminishing closer to the original W' value. It is also of note that half time for lactate clearance were slower than W', but faster for $VO_2$. In an effort to better understand these observations, Chidnok et al. (2012) compared severe intensity intermittent cycling and resultant recovery using the model suggested by Morton and Billat (2004), changing only $P_r$. Confirming the early assumption of W' recovery, time to exhaustion increased in response to the difference between $P_r$ and CP, only observing an increase in time for $P_r$ below CP (Chidnok et al., 2012). Furthermore, in agreement with Ferguson et al. (2010), a greater difference between $P_r$ and CP resulted in greater recovery of W', though still curvilinear (Chidnok et al., 2012).

#### *2.1.6.2 Modelling reconstitution kinetics of W'*

The current stage of research on the kinetics of W' recovery is centered around Skiba et al. (2012) proposed $W_{bal}$ model, which accounts for the varied reconstitution of W' as has been suggested by earlier studies (Chidnok et al., 2012; Ferguson et al., 2010; Jones et al., 2008; Morton & Billat, 2004). This model has successfully predicted W' at the end of exercise (Skiba et al., 2015; Skiba et al., 2014), but have later been criticised for not considering varying recovery intensity and its limited potential during exercise (Bartram et al., 2018). A later study by Skiba et al. (2015) improves upon the original model by Skiba et al. (2012), formulating a time constant for assessing exponential reconstitution of W' below CP.

While the framework for tracking W' has been considered to be suitable, Bartram et al. (2018) have questioned the validity of the time constant regulating the variable reconstitution of W', suggesting a difference in recovery for different populations. Assessing this hypothesis, they demonstrated the previous model to underestimate recovery in elite athletes, suggesting a modified time constant as more appropriate for elite populations. However, further validation of the modified time constant is needed to assess general applicability (Bartram et al., 2018), or if the time constant should be calculated on an individual basis (Skiba et al., 2015). Whilst the $W_{bal}$ have been successfully applied (Broxterman et al., 2016; Townsend et al., 2017; Vassallo, Gray, Cummins, Murphy, & Waldron, 2020), recent studies have implicated both a fatiguing effect in the recovery kinetics and variable rate of reconstitution in response to rate of depletion (Caen et al., 2019; Chorley, Bott, Marwood, & Lamb, 2019). This suggests the kinetics of W' to change in response to the characteristics of exercise. Therefore, at the time of writing, we are not able to consistently predict the state or value of W' with enough precision to assess dynamic changes during a race (Bartram et al., 2018; Chorley et al., 2019; Jones & Vanhatalo, 2017; Skiba et al., 2015; Townsend et al., 2017; Vassallo et al., 2020). Nevertheless, the CP framework could still provide practical information regarding the physiological load of exercise, without access to measurement of lactate and/or $VO_2$ (Jones & Vanhatalo, 2017).

## *2.2 Cross-country mountain biking*

### *2.2.1 Characteristics*

Cross-country mountain biking are mass-start races designed to last 80-100 min, where a trail of 4-6 km of varied off-road terrain is repeatedly conducted with the goal of crossing the finish line first (UCL regulations). A XCO-MTB race include both up- and downhill technical segments composed of forest paths, technical rocky descents, jumps etc. which have consequences for both external stress, psychological and physiological requirements for practitioners (Granier et al., 2018).

A fundamental part of XCO-MTB is the intensive mass-start. Athletes race through a "start loop" [SL] during the initial minutes of the race, this is an independent segment of the overall track, featuring a more open area than the rest of the race. As the athletes reach the start of the first lap, passing other athletes becomes more difficult as a result of narrowing segments and technical requirements of the track, which makes securing a beneficial position during the opening mass-start of the race crucial (Granier et al., 2018). It is of interest for better riders to avoid cycling behind a potentially slower rider even if drifting could conceivably reduce energy expenditure (Impellizzeri & Marcora, 2007), as it might also increase difficulty of traversing technical obstacles, increasing breaking and hindering strategic pacing (Miller, Fink, Macdermid, Allen, & Stannard, 2018; Miller, Fink, Macdermid, & Stannard, 2019). Macdermid and Morton (2012) have presented position in the starting grid to be an important denominator for the finishing position.  Indeed, international competition position better riders further towards the front based on UNI World ranking, which certainly incentivise the aggressive opening to secure a better position in the field (Granier et al., 2018; Macdermid & Morton, 2012; Macdermid & Stannard, 2012; Viana et al., 2018).

### *2.2.2 Exercise intensity*

Studies on XCO-MTB intensity have classically been assessed using HR, PO and speed, with later studies also evaluating race- and lap time to analyse the workload (Granier et al., 2018; Impellizzeri & Marcora, 2007). Heart rate have displayed an average of over 90% of $HR_{max}$ during competition (Granier et al., 2018; Impellizzeri et al., 2002; Stapelfeldt, Schwirtz, Schumacher, & Hillebrecht, 2004) along with consistent high intensity of HR exhibited through 80% of the race performed above lactate threshold (Impellizzeri et al., 2002).  The same general high intensity is also evident through average PO and speed, ranging from 234 – 284 W (Granier et al., 2018; Macdermid & Stannard, 2012) 14-19.7 km/h  (Granier et al., 2018; Martin et al., 2012), respectively. While these classic lap-to-lap parameters can provide an overview, critical information is lost regarding the intermittent workload in XCO-MTB. On this, Hays et al. (2018) have recently reported a considerable portion of work performed above the second ventilatory threshold [VT2] and even beyond maximal aerobic power, comparing physiological responses to that of intermittent team sports. This is supported by Granier et al. (2018), presenting comparable results accompanied by a highly stochastic PO, consistent across a season of competition.

Recent investigations have indicated exercise intensity to be higher than what is evident through PO alone, with descents (Miller, Macdermid, Fink, & Stannard, 2017), upper-body work (Hurst et al., 2012; Macdermid, Fink, & Stannard, 2014) and braking (Miller et al., 2018) as potential influencers of fatigue. This could be a possible explanation for the observed disconnect between PO and $VO_2$ readings by Hays et al. (2018), consistently displaying greater intensity in continuous $VO_2$ measures, particularly after climbs and beginning of descents. The substantial variation in PO reported by Granier et al. (2018) and the sheer number of actions representing the 28% of race time above map reported by Hays et al. (2018), exemplifies the intermittent high intensity required by XCO-MTB.

Taken together, the intermittent nature of XCO-MTB races certainly requires a well-developed aerobic capacity to sustain the high intensity, with significant utilization of anaerobic power during crucial moments of the sport.

### *2.2.3 Performance*

The complex nature of XCO-MTB has led to a plethora of characteristics being investigated as potential determinants of performance. A landmark study by Impellizzeri et al. (2005b) investigate relationship between multiple tests of aerobic fitness and performance in XCO-MTB, presenting both maximal and submaximal aerobic indices as crucial for performance. Furthermore, they suggested relative measures of performance parameters to better fit the characteristics of the sport, because of the repeated climbs in the track circuit (Impellizzeri et al., 2005a).

To further investigate relative physiological characteristics, Impellizzeri et al. (2005a) tested internationally competitive athletes for $VO_{2max}$, peak power output, PO and oxygen uptake at ventilatory thresholds 1[VT1] and 2[VT2]. Curiously, the correlations were only suited for performance prediction when normalised to body mass (Impellizzeri et al., 2005a). While PO and Oxygen uptake at VT2 correlated to performance; VT 1, $VO_{2max}$ and PPO did not. They concluded that submaximal thresholds allowing for maintenance of a high intensity holds more sway in XCO-MTB performance than maximal indicators such as PPO and $VO_{2max}$. This further cemented mass-to-power ratio, especially for higher level competitive athletes (Impellizzeri et al., 2005a).

Considering the reports of relative OBLA and respiratory compensation point significantly correlating to race time (Impellizzeri et al., 2005a; Impellizzeri et al., 2005b) as well as the reported validity of FTP and Intermittent power (Miller et al., 2014), this could indicate a positive impact on performance by having increasing the threshold between aerobic and anaerobic metabolism (Viana et al., 2018). Viana et al. (2018) have recently presented similar lap-to-lap declines PO relative to OBLA for a high and a low performance group. Suggesting a direct increase in PO with increase in relative OBLA, supporting the role of OBLA threshold as a determinant for performance.

To the contrary, Prins, Terblanche, and Myburgh (2007) presented conflicting results regarding relative OBLA, displaying significant correlations for an outdoor XCO-MTB trial but not for XCO-MTB competition. They propose that the presence of competitors could alter tactical decisions and therefore reduce the significance of innate physiological ability. To this end, Novak et al. (2018) have demonstrated decision making to significantly contribute to precision of predictive models for XCO-MTB, suggesting that while uphill sections rely on aerobic capacity and anaerobic power, effective decision making chiefly impact high-speed downhill sections which are not well accounted for by PO data (Hays et al., 2018; Macdermid et al., 2014). This is further substantiated by Hays et al. (2018), showing intensity after climbs and in technical descents to be higher than what is evident from PO. A study on descents in XCO-MTB also demonstrates substantial differences in intensity for different descending strategies (Miller et al., 2017), potentially as a result of vibration dampening and upper body work (Hurst et al., 2012; Macdermid et al., 2014). This might prevent recovery that could take place during non-power producing sections and increase intensity beyond what is inferred from PO (Hurst et al., 2012; Macdermid et al., 2014; Miller et al., 2017).

Ultimately, elite XCO-MTB athletes typically display excellent relative physiological characteristics with high cardiovascular capabilities (Granier et al., 2018; Gregory et al., 2007; Impellizzeri & Marcora, 2007). Determinants for performance are complex, but research show that capabilities for withstanding an overall high intensity (Granier et al., 2018; Hays et al., 2018; Impellizzeri et al., 2002; Viana et al., 2018), produce PO in excess of MAP (Granier et al., 2018; Hays et al., 2018) and well-developed technical ability (Macdermid et al., 2014; Miller et al., 2018; Miller et al., 2017; Novak et al., 2018), all contribute to end performance.

### *2.2.4 Pacing*

Cross-country mountain biking is a high-speed intermittent sport where the goal is to complete the course as fast as possible. With a finite ability to generate power, it is of great interest to distribute available work efficiently across the race (Tucker & Noakes, 2009). The pacing, or pacing strategy, of an athlete is generally considered to be the distribution of available energy throughout a task (Abbiss & Laursen, 2008). In XCO-MTB, pacing specifically refers to the allocation of speed and PO, challenged by the presence of other riders and the varied off-road track structure (Abbiss et al., 2013). The pacing strategy is the overall distribution an athlete chooses to employ over the course of a race, optimally resulting in expenditure of all available energy by the end of the race without adversely affecting speed or PO (Tucker & Noakes, 2009). While preventing homeostatic disturbance which could prematurely end exercise is one of the goals of pacing, strategic variation in the recovery and increase of mechanisms responsible for metabolic disturbance could be favourable for performance in head-to-head competition (Tucker & Noakes, 2009). Given the peculiar format of XCO-MTB, pacing is prominent in analysis of the sport, and a substantial influence on performance (Abbiss & Laursen, 2008; Abbiss et al., 2013; Impellizzeri et al., 2002).

### *2.2.5 Pacing in XCO-MTB*

There are several studies examining pacing adopted by athletes in XCO MTB races, employing different methods of measurement. An overview of studies assessing pacing in XCO-MTB are presented in table 2.1. Abbiss et al. (2013) demonstrated that initial laps had a high speed which then gradually dissipated over the course of the race, indicative of a positive pacing strategy. Interestingly, the top elite performers adopted a more even-pacing following the fast start, supporting the general perception that even-pacing is the optimal strategy for cycling endurance competition (Abbiss & Laursen, 2008; Abbiss et al., 2013; Swain, 1997). The theory that athletes attempt to maintain an even-pacing throughout a race is further supported by Martin et al. (2012), who postulated an even-between lap pacing despite large intralap variations. Moreover, there is some evidence suggesting elite athletes are better able to maintain an even pace across laps, more effectively resisting deterioration from the heavy intensity during SL and the initial laps (Abbiss et al., 2013; Granier et al., 2018; Impellizzeri et al., 2002).

On the other hand, Viana et al. (2018) reported an equal decline in intensity for both high- and low performers, suggesting the higher inherent physiological characteristics determine performance. However, the extended period of testing and high level athletes in Granier et al. (2018) study makes their assessment convincing, though this should be investigated further.

Overarching pacing strategy is thought not to fully describe the workload in XCO-MTB, because of the large intralap variations in response to varying external conditions (Granier et al., 2018; Martin et al., 2012). Martin et al. (2012) suggest a largely spontaneous relationship between the pacing applied and terrain which results in the characteristic intermittent workload. Recent studies corroborate this, presenting a continual high frequency of high intensity actions (Granier et al., 2018; Hays et al., 2018). Though it is presented that even with a high percent of lap time above MAP, the decline in intensity stem from a decrease in above MAP actions, possibly as a result of less density of competitors (Granier et al., 2018; Hays et al., 2018). Because of this, future studies should aim to better explain lap-to-lap and intralap evolution of pacing in specific parts of a course, specifically in ascents and descents (Hays et al., 2018; Martin et al., 2012).

The fast start followed by even-pacing described by several studies (Abbiss et al., 2013; Granier et al., 2018; Hays et al., 2018; Impellizzeri et al., 2002; Viana et al., 2018), have ultimately been proposed as a response to the race format (Granier et al., 2018). As XCO-MTB athletes are heavily encouraged to adopt a high pace during initial stages of the race to optimally position themselves in the field and retain a high pace until there is a reduced density of riders (Abbiss et al., 2013; Granier et al., 2018; Macdermid & Morton, 2012). Indeed, hindrance of other athletes during technical segments might heighten physiological load and influence decision-making (Miller et al., 2017; Novak et al., 2018; Tucker & Noakes, 2009). Building on this, optimizing technical segments and descents could limit braking and subsequent reacceleration, potentially leading to a more even-across lap pacing (Macdermid et al., 2014; Miller et al., 2017; Novak et al., 2018).

*Table 2-1* Overview on literature assessing pacing strategy in XCO-MTB

| Study | Subjects (n) | Level | Style | Measure | Pacing |
|---|---|---|---|---|---|
| Martin et al. (2012) | 5/1 | Regional | SIM | Continuous speed | EVE |
| Abbiss et al. (2013)* | X* | X* | COMP | Time | POS/EVE |
| Hays et al. (2018) | 16 | National/Elite Jr. | SIM | PO/$VO_2$/HR | F-EVE |
| Granier et al. (2018) | 8 | Olympic | COMP | PO/Speed/HR | F-EVE |
| Viana et al. (2018) | 20 | Trained | SIM | Time/ HR/SPEED/ Estimated PO | POS/EVE |

X*: Data on all participants in 2009 UCI Cross-Country Mountain Bike World Champion in different categories; Elite Male, n=75; Elite Female, n=50; Under 23 Male, n=62; Under 23 Female, n= 34, Junior Male, n =71; Junior Female, n= 30
**LtL** = lap-to-lap comparison; **SIM** = simulated competition; **POS** = positive pacing; **EVE** = Even-pacing; **F-EVE** = Fast start followed by even pacing;

## 2.3 Assessment of power output

The current study will assess CP using the participants own bicycle with the accompanying power-meter, mounted on a WAHOO KICKR. Appendix 1 display the reliability measures of the WAHOO KICKR in this study. Portable power meters are generally accepted as reliable measuring devices (Miller, Macdermid, Fink, & Stannard, 2016; Passfield, Hopker, Jobson, Friel, & Zabala, 2017), but have some inherent limitations. The accuracy of individual power meters can change based on position, friction, insufficient maintenance, low changes in revolution and calibration (Passfield et al., 2017). The reliability of power meters has been verified for use in cross-country mountain biking but may depend on each units ability fast and accurately respond to changes in cadence (Miller et al., 2016). Moreover, the validity of direct comparison between different power meters when measuring performance changes down to 1% have been questioned (Maier, Schmid, Muller, Steiner, & Wehrlin, 2017). The difference between power output recorded in Wahoo and participants power meter is presented in Table 2-2. It is evident that there is a large interunit variability, with differences between wahoo and the power meter ranging from 3.7 to 23.8 %. Despite the large range, there is a very slight difference between the test days for each individual power meter. The portable power meters therefore proved reliable, but with some discrepancies regarding valid output.

*Table 2-2 Average difference for all tests between WAHOO and participants power meter in percent*

| | Avg. Difference day 1 | Avg. Difference day 2 | Difference in mean (Diff 2- Diff 1) |
|---|---|---|---|
| FP02 | 21.7 ± 2 | 23.8 ± 3.4 | 2.06 |
| FP03 | 10.1 ± 2 | 9.1 ± 1.7 | -0.95 |
| FP04 | 13.2 ± 1.5 | 13.6 ± 1.3 | 0.42 |
| FP05 | 4.5 ± 0.6 | 6.5 ± 0.6 | 2.01 |
| FP07 | 6.1 ± 1.3 | 3.7 ± 1.2 | -2.37 |
| FP08 | 5.5 ± 0.8 | 5.5 ± 0.5 | -0.01 |
| Total | 10.2 ± 6 | 10.4 ± 6.8 | 0.19 |

## 2.4 Summary

In XCO-MTB multiple factors have profound impact on performance. The characteristics of the sport require a wide range of inherent physiological factors to navigate the intensive mass-start, high intra-lap variations and the substantial exercise intensity. Balancing exercise intensity throughout the race to one's best ability require technical ability and mental acuity along with a high tolerance of intermittent high intensity exercise. Previous studies have displayed that a high-power output in relation to the power at onset of blood lactate accumulation as a determining factor for performance in elite athletes. Given that the onset of blood lactate accumulation has displayed great correlation with the Critical Power threshold, we set out to assess the applicability of this parameter to better describe physiological workload in XCO-MTB based on power output (Viana et al., 2018; Miller & Macdermid, 2015) . This could potentially increase the validity of using a portable power meter to track performance in XCO-MTB for athletes and coaches, as the greatest method for tracking exercise performance for coaches and athletes, is the one that's actually used.

# 3 Methods

### *3.1.1 Participants*

A total of eight XCO-MTB athletes were recruited for this study, all competing at a national level. Table 3-1 displays the subject characteristics for this study. Inclusion criteria were as follows:

(1) participation in a specified national XCO-MTB race

(2) access to a portable power meter for use during the race and post-race testing.

All participants completed the race; however, one was excluded from further analysis due to absence from post-testing.  Prior to data collection, each participant gave written informed consent to participate in the study. The protocol was approved by the local ethics committee of the Norwegian School of Sport Sciences. The study was reported to the Norwegian Centre for Research Data and the was conducted in accordance to the Declaration of Helsinki and GDPR.

***Table 3-1*** *Subject anthropometry and characteristics an at baseline (n=7)*

| | **Mean** | **Range** |
|---|---|---|
| Age (yr) | 23 | 19 - 31 |
| Body mass (kg) | 69 | 61 - 88 |
| Height (cm) | 178 | 161 - 198 |
| $VO_{2max}$ ($ml*min^{-1}*kg^{-1}$) | 71 | 59 - 79 |
| $VO_{2max}$($L*min^{-1}$) | 4.9 | 3.7 - 6.0 |
| mean PO 30-sec test(W) | 754 | 448 - 991 |
| PPO 30-sec test (W) | 963 | 546 - 1282 |
| MAP (W) | 397 | 267 - 568 |
| CP (W) | 329 | 241 - 456 |

### 3.1.2 General design

This study required participants to partake in three sessions, the first of which was an official XCO race (Karl XII rittet NC10, Norway, UCI cat 1, Rundbane), and thereafter reported to the lab on two occasions separated by at least 48 h. The official XCO race was already a part of the participants competitive schedule when they were recruited. The men and women competed in different races, but on the same track, at the same time of day.

Participants height and body mass were measured at the start of each indoor testing day, then completed a short motivation questionnaire pre- and post-testing. The participants three submaximal workloads and four performance tests on each lab day, to estimate MAP, maximal power over 30 seconds and estimate CP. All athletes used the same bike and power meter (Quarq N=6, 4iiii N=1) on indoor tests as used during the race, mounted on a cycling ergometer. Subjects were instructed to use the power and cadence feedback from their personal cycling computer. Power and cadence were recorded with their personal power meter and used for further analysis. Participants performed two test days to determine the power-duration relationship, with the first day serving as a familiarization as proposed by Triska et al. (2017). $VO_2$ data for TT were only recorded for the second test day, the days were otherwise identical and is shown in figure 3-1.

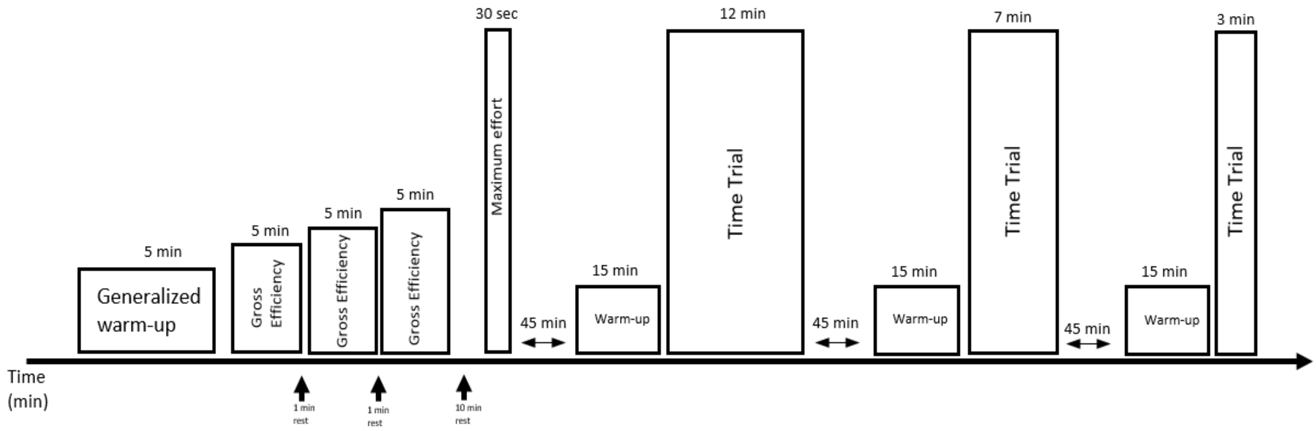


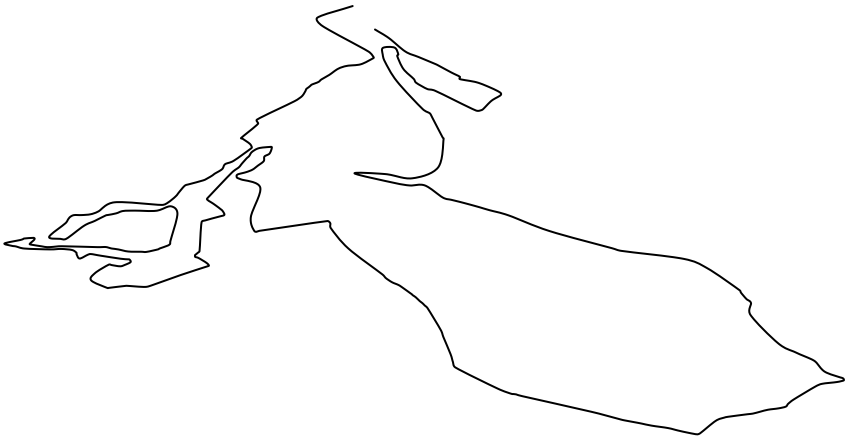

***Figure 3-1**: Illustration of test protocol for submaximal workloads and performance tests conducted on the indoor test days on subjects' personal bike. Three submaximal workloads; 150, 200 and 250W for men and 125, 175, 195 W women, respectively. Followed by performance tests beginning with a 30 seconds all-out test before a 12 min TT, a 7 min TT and a 3 min TT in that order. All performance tests following the 30 seconds maximal test were separated by 45 min rest and 15 min warm-up.*

## 3.2 Competition testing

Participants competed in an official regional XCO-MTB race "Karl XII rittet NC10, UCI cat 1, Rundbane (XCO)", and were to complete the race as they would have otherwise. A single circuit of the track included uphill and downhill sections with a total length of 3.8 km, with 101 m climb and 99 m descent based as reported by race organizers (FIGURE 3-2). Round times, power output, heartrate and speed data were recorded during the race as well as a short motivation questionnaire pre- and post-race.

No further information was given to participants prior to competition. The number of laps differed between genders, 6 for males and 5 for females. In order to compare data from all participants, we divided the race into following parts: start loop (SL), round 1 (R1), round 2 (R2), round 3(R3), the second to last lap (Ln-1), and final lap (LN), similar to Granier et al. (2018). Efforts exerted above CP were divided into three categories based on magnitude: From CP to 1.5*CP [P1],1.5*CP to 2*CP[P2] and 2*CP and above [P3]. In addition, actions above CP were subdivided into five groups based duration: 1 -5 s[TS1], 6-10 s[TS2], 11-15 s[TS3], 16-20 s[TS4] and >21 s [TS5]. Data were recorded at a frequency of 1 Hz and transmitted to each participant's personal cycling computer.

**A**



**B**

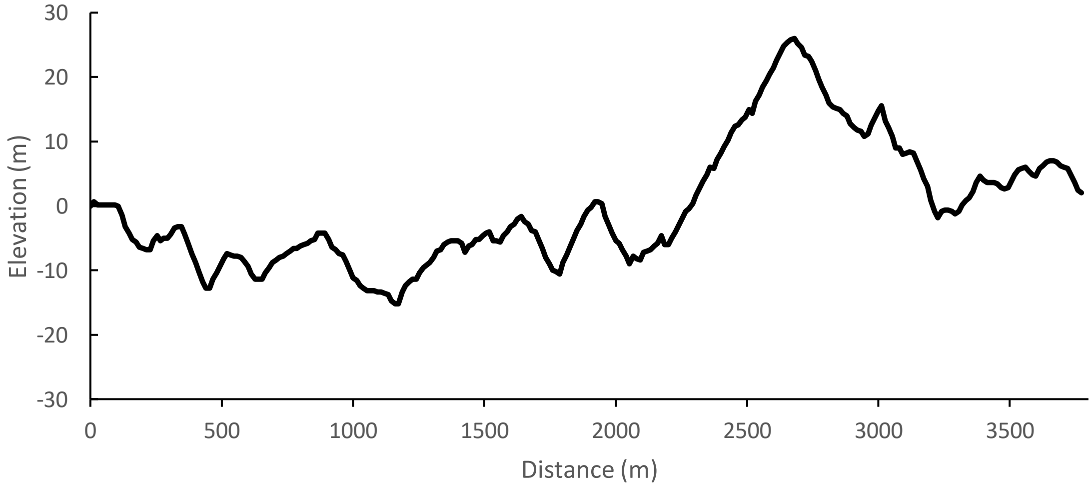



***Figure 3-2*** *Graphical presentation of Lap outline and profile (A) topographic illustration of lap path. (B) Altitude through one round of the track*

## 3.3 Indoor testing

### Submaximal test

On each test day, each participant completed a 10-minute warm-up (range 50 - 150W) before a submaximal, incremental exercise test to determine individual relationship between external power production and $VO_2$. The test consisted of 5-min steps at work rates 150, 200, and 250 W for men and 125, 175, 195 W for women, with 1-minute breaks between each of the work-rates. Participants were free to choose their preferred cadence but were instructed to maintain chosen cadence during all tests. $VO_2$, RER, and HR were measured during the last 2.5 min as well as the athletes Rate of perceived exhaustion using Borgs 6 to 20 scale (1970) at the end of each step. The participants were instructed to remain seated and maintain a consistent cadence which would also be used in the TT. The submaximal work rates corresponded to 46 ± 7, 57±10.2 and 68±10% of $VO_{2peak}$ achieved during the TT.

External power from the power meter and $VO_2$ were the main assessment measures for the submaximal workloads. HR and RPE was recorded immediately following completion of each workload.

### Performance tests

Following 10 minutes active rest, a maximal all-out cycling test was performed to determine the maximal power output over 30 seconds for each participant. Subjects were asked to perform 30 second all-out effort, starting from a standstill similar to the mass-start of a XCO-MTB race. A 5 second countdown initiated the test and participants were strongly encouraged to accelerate as much as possible and maintain maximal power output. Subjects were instructed to remain seated throughout the test. Participants were free to change the ergometer resistance on the virtual gear changer throughout the test. Following the test they were allowed up to 10 min active recovery before the 45 min rest period to the remaining performance tests.

CP and W' were established using three maximum effort time trials of 12[TT12], 7 [TT7] and 3[TT3] minutes in that order, as suggested by Karsten et al. (2018).
Before each TT a 15 min warm-up was completed with light intensity from start to 7 min, followed by medium-high intensity from min 7 to 10 and finishing with a 5 min light intensity from min 10 to 15. TT's were started from standstill and quickly accelerated up to a work rate the participants predict they could sustain for the length of

each TT but were free to adjust the ergometer resistance as in the previous test. Participants were instructed to maintain their previously chosen cadence throughout the TT. Feedback on time left and strong verbal encouragement were provided during the test. After each TT the participant were allowed 10 min active recovery before proceeding to 45 min passive rest. The first indoor day was used as familiarization and $VO_2$ for TT's were therefore only recorded on the second day. To combat a negative pacing strategy, a forced watt was set on the TTs for the second day, locking watt-resistance for 1 min at the beginning of the 12min and 7 min TT, and for 30sec for the 3 min TT. Watt was locked at the mean watt produced on the familiarization day, and subjects were free to adjust resistance as usual after the lock.

### *Maximal aerobic power*

$VO_2$ and PO was used to assess work during submaximal workloads from which linear regression was used to extrapolate the power corresponding to Maximal aerobic power [MAP].

### *Calculation of CP and the W' parameter*

Linear regression was used to find the CP and W' plotting mean effect against the inverse of time using the P =W' [1/t] + CP) model.

Power output measured above CP during the different laps was normalised to CP and divided into three power zones, watt corresponding to CP to 1.5 times CP[P1], 1.5 to 2 times CP[P2], and >2 times CP[P3]. Efforts above CP were divided into 5 categories based on duration: 1–5 s[TS1], 6–10 s[TS2], 11–15 s[TS3], 16–20 s[TS4], and efforts above 21 s[TS5].

### *Data capture*

Post-testing all exercise trials, power output and cadence were downloaded into cycling desktop software Golden Cheetah (Golden Cheetah training software, goldencheetah.org). Data were subsequently exported to Microsoft Office Excel 365 (Microsoft, Redmond, USA) for further analysis.

### *Statistical*

Test data for normality with a Shapiro-Wilk test and by visual inspection. Unless otherwise specified, data are displayed as mean + range. Between lap differences are displayed as mean + standard deviation and 95% Confidence Intervals. A paired T-test were used to investigate if there are significant differences between the physiological parameters, CP and average watt during the indoor test-days. One-way Repeated ANOVA with Bonferroni correction for multiple comparisons were performed to identify any statistically significant difference between laps using % of time above CP, % of time above MAP, actions above CP, $km*h^{-1}$, CAD, avg HR as dependent variables. If the assumption of sphericity had been violated the Greenhouse-Geisser correction has been used. The statistical significance level was set at $p = 0.05$, and analyses were performed in SPSS Statistics (IBM Corp., Armonk, NY).

# 4 References


Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med, 38*(3), 239-252. doi:10.2165/00007256-200838030-00004

Abbiss, C. R., Ross, M. L., Garvican, L. A., Ross, N., Pottgiesser, T., Gregory, J., & Martin, D. T. (2013). The distribution of pace adopted by cyclists during a cross-country mountain bike World Championships. *J Sports Sci, 31*(7), 787-794. doi:10.1080/02640414.2012.751118

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med, 26*(4), 217-238. doi:10.2165/00007256-199826040-00002

Bailey, S. J., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009). Influence of repeated sprint training on pulmonary O2 uptake and muscle deoxygenation kinetics in humans. *J Appl Physiol (1985), 106*(6), 1875-1887. doi:10.1152/japplphysiol.00144.2009

Barker, T., Poole, D. C., Noble, M. L., & Barstow, T. J. (2006). Human critical power-oxygen uptake relationship at different pedalling frequencies. *Exp Physiol, 91*(3), 621-632. doi:10.1113/expphysiol.2005.032789

Barstow, T. J., Jones, A. M., Nguyen, P. H., & Casaburi, R. (1996). Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. *J Appl Physiol (1985), 81*(4), 1642-1650. doi:10.1152/jappl.1996.81.4.1642

Bartram, J. C., Thewlis, D., Martin, D. T., & Norton, K. I. (2018). Accuracy of W' Recovery Kinetics in High Performance Cyclists-Modeling Intermittent Work Capacity. *Int J Sports Physiol Perform, 13*(6), 724-728. doi:10.1123/ijspp.2017-0034

Bishop, D., & Jenkins, D. G. (1995). The influence of recovery duration between periods of exercise on the critical power function. *European journal of applied physiology and occupational physiology, 72*(1-2), 115-120.

Black, M. I., Jones, A. M., Blackwell, J. R., Bailey, S. J., Wylie, L. J., McDonagh, S. T., . . . Vanhatalo, A. (2017). Muscle metabolic and neuromuscular determinants of fatigue during cycling in different exercise intensity domains. *J Appl Physiol (1985), 122*(3), 446-459. doi:10.1152/japplphysiol.00942.2016

Broxterman, R. M., Ade, C. J., Poole, D. C., Harms, C. A., & Barstow, T. J. (2013). A single test for the determination of parameters of the speed-time relationship for running. *Respir Physiol Neurobiol, 185*(2), 380-385. doi:10.1016/j.resp.2012.08.024

Broxterman, R. M., Skiba, P. F., Craig, J. C., Wilcox, S. L., Ade, C. J., & Barstow, T. J. (2016). W' expenditure and reconstitution during severe intensity constant power exercise: mechanistic insight into the determinants of W'. *Physiol Rep, 4*(19), 1-9. doi:10.14814/phy2.12856

Bull, A. J., Housh, T. J., Johnson, G. O., & Rana, S. R. (2008). Physiological responses at five estimates of critical velocity. *Eur J Appl Physiol, 102*(6), 711-720. doi:10.1007/s00421-007-0649-7

Burnley, M., & Jones, A. M. (2007). Oxygen uptake kinetics as a determinant of sports performance. *European Journal of Sport Science, 7*(2), 63-79. doi:10.1080/17461390701456148

Caen, K., Bourgois, J., Bourgois, G., Van der Stede, T., Vermeire, K., & Boone, J. (2019). The reconstitution of W′ depends on both work and recovery characteristics. *Medicine & Science in Sports & Exercise, 51*(8), 1745-1751.

Chidnok, W., Dimenna, F. J., Bailey, S. J., Vanhatalo, A., Morton, R. H., Wilkerson, D. P., & Jones, A. M. (2012). Exercise tolerance in intermittent cycling: application of the critical power concept. *Med Sci Sports Exerc, 44*(5), 966-976. doi:10.1249/MSS.0b013e31823ea28a

Chidnok, W., Dimenna, F. J., Bailey, S. J., Wilkerson, D. P., Vanhatalo, A., & Jones, A. M. (2013a). Effects of pacing strategy on work done above critical power during high-intensity exercise. *Med Sci Sports Exerc, 45*(7), 1377-1385. doi:10.1249/MSS.0b013e3182860325

Chidnok, W., DiMenna, F. J., Fulford, J., Bailey, S. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013b). Muscle metabolic responses during high-intensity intermittent exercise measured by (31)P-MRS: relationship to the critical power concept. *Am J Physiol Regul Integr Comp Physiol, 305*(9), R1085-1092. doi:10.1152/ajpregu.00406.2013

Chorley, A., Bott, R. P., Marwood, S., & Lamb, K. L. (2019). Slowing the Reconstitution of W' in Recovery With Repeated Bouts of Maximal Exercise. *Int J Sports Physiol Perform, 14*(2), 149-155. doi:10.1123/ijspp.2018-0256

Clark, I. E., West, B. M., Reynolds, S. K., Murray, S. R., & Pettitt, R. W. (2013). Applying the critical velocity model for an off-season interval training program. *J Strength Cond Res, 27*(12), 3335-3341. doi:10.1519/JSC.0b013e31828f9d87

Clarke, A. C., Presland, J., Rattray, B., & Pyne, D. B. (2014). Critical velocity as a measure of aerobic fitness in women's rugby sevens. *Journal of Science and Medicine in Sport, 17*(1), 144-148.

Coats, E. M., Rossiter, H. B., Day, J. R., Miura, A., Fukuba, Y., & Whipp, B. J. (2003). Intensity-dependent tolerance to exercise after attaining V(O2) max in humans. *J Appl Physiol (1985), 95*(2), 483-490. doi:10.1152/japplphysiol.01142.2002

de Koning, J. J., Bobbert, M. F., & Foster, C. (1999). Determination of optimal pacing strategy in track cycling with an energy flow model. *J Sci Med Sport, 2*(3), 266-277. doi:10.1016/s1440-2440(99)80178-9

De Lucas, R., De Souza, K., Costa, V., Grossl, T., & Guglielmo, L. (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.

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*(3-4), 281-288. doi:10.1007/s00421-002-0786-y

Dekerle, J., Mucci, P., & Carter, H. (2012). Influence of moderate hypoxia on tolerance to high-intensity exercise. *Eur J Appl Physiol, 112*(1), 327-335. doi:10.1007/s00421-011-1979-z

Ferguson, C., Rossiter, H. B., Whipp, B. J., Cathcart, A. J., Murgatroyd, S. R., & Ward, S. A. (2010). Effect of recovery duration from prior exhaustive exercise on the parameters of the power-duration relationship. *J Appl Physiol (1985), 108*(4), 866-874. doi:10.1152/japplphysiol.91425.2008

Ferretti, G. (2014). Maximal oxygen consumption in healthy humans: theories and facts. *Eur J Appl Physiol, 114*(10), 2007-2036. doi:10.1007/s00421-014-2911-0

Florence, S. L., & Weir, J. P. (1997). Relationship of critical velocity to marathon running performance. / Relation entre la velocite critique et la performance au marathon. *European Journal of Applied Physiology & Occupational Physiology, 75*(3), 274-278.

Gloersen, O., Gilgien, M., Dysthe, D. K., Malthe-Sorenssen, A., & Losnegard, T. (2020). Oxygen Demand, Uptake, and Deficits in Elite Cross-Country Skiers during a 15-km Race. *Med Sci Sports Exerc, 52*(4), 983-992. doi:10.1249/MSS.0000000000002209

Granier, C., Abbiss, C. R., Aubry, A., Vauchez, Y., Dorel, S., Hausswirth, C., & Le Meur, Y. (2018). Power Output and Pacing During International Cross-Country Mountain Bike Cycling. *Int J Sports Physiol Perform, 13*(9), 1243-1249. doi:10.1123/ijspp.2017-0516

Gregory, J., Johns, D. P., & Walls, J. T. (2007). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *J Strength Cond Res, 21*(1), 17-22. doi:10.1519/00124278-200702000-00004

Haseler, L. J., Kindig, C. A., Richardson, R. S., & Hogan, M. C. (2004). The role of oxygen in determining phosphocreatine onset kinetics in exercising humans. *J Physiol, 558*(Pt 3), 985-992. doi:10.1113/jphysiol.2004.062042

Hays, A., Devys, S., Bertin, D., Marquet, L. A., & Brisswalter, J. (2018). Understanding the Physiological Requirements of the Mountain Bike Cross-Country Olympic Race Format. *Front Physiol, 9*(AUG), 1062. doi:10.3389/fphys.2018.01062

Hill, A. V. (1927). Muscular Movement in Man: The Factors Governing Speed and Recovery from Fatigue. *Muscular Movement in Man: the Factors governing Speed and Recovery from Fatigue.*

Hill, D. W. (1993). The critical power concept. A review. *Sports Med, 16*(4), 237-254. doi:10.2165/00007256-199316040-00003

Hoon, M., Michael, S., Chapman, P., & 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. Retrieved from https://www.researchgate.net/publication/313881132

Hurst, H., Hurst, H. T., Swarén, M., Hébert-Losier, K., Ericsson, F., Sinclair, J., . . . Holmberg, H.-C. (2012). Influence of course type on upper body muscle activity in elite Cross-Country and Downhill mountain bikers during off Road Downhill Cycling. *Journal of Science and Cycling, 1*(2), 2-9. doi:10.28985/jsc.v1i2.20

Impellizzeri, F., Sassi, A., Rodriguez-Alonso, M., Mognoni, P., & Marcora, S. (2002). Exercise intensity during off-road cycling competitions. *Med Sci Sports Exerc, 34*(11), 1808-1813. doi:10.1097/00005768-200211000-00018

Impellizzeri, F. M., & Marcora, S. M. (2007). The physiology of mountain biking. *Sports Med, 37*(1), 59-71. doi:10.2165/00007256-200737010-00005

Impellizzeri, F. M., Marcora, S. M., Rampinini, E., Mognoni, P., & Sassi, A. (2005a). Correlations between physiological variables and performance in high level cross country off road cyclists. *Br J Sports Med, 39*(10), 747-751. doi:10.1136/bjsm.2004.017236

Impellizzeri, F. M., Rampinini, E., Sassi, A., Mognoni, P., & Marcora, S. (2005b). Physiological correlates to off-road cycling performance. *J Sports Sci, 23*(1), 41-47. doi:10.1080/02640410410001730061

Inoue, A., Sa Filho, A. S., Mello, F. C., & Santos, T. M. (2012). Relationship between anaerobic cycling tests and mountain bike cross-country performance. *J Strength Cond Res, 26*(6), 1589-1593. doi:10.1519/JSC.0b013e318234eb89

Jenkins, D. G., Kretek, K., & Bishop, D. (1998). The duration of predicting trials influences time to fatigue at critical power. *Journal of Science and Medicine in Sport, 1*(4), 213-218.

Jenkins, D. G., & Quigley, B. M. (1992). Endurance training enhances critical power. *Med Sci Sports Exerc, 24*(11), 1283-1289. Retrieved from https://www.ncbi.nlm.nih.gov/pubmed/1435180

Jones, A. M., Burnley, M., Black, M. I., Poole, D. C., & Vanhatalo, A. (2019). The maximal metabolic steady state: redefining the 'gold standard'. *Physiol Rep, 7*(10), e14098. doi:10.14814/phy2.14098

Jones, A. M., & Vanhatalo, A. (2017). The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. *Sports Med, 47*(Suppl 1), 65-78. doi:10.1007/s40279-017-0688-0

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of V O2max and exercise tolerance. *Med Sci Sports Exerc, 42*(10), 1876-1890. doi:10.1249/MSS.0b013e3181d9cf7f

Jones, A. M., Wilkerson, D. P., DiMenna, F., Fulford, J., & Poole, D. C. (2008). Muscle metabolic responses to exercise above and below the "critical power" assessed using 31P-MRS. *Am J Physiol Regul Integr Comp Physiol, 294*(2), R585-593. doi:10.1152/ajpregu.00731.2007

Karsten, B., Baker, J., Naclerio, F., Klose, A., Bianco, A., & Nimmerichter, A. (2018). Time Trials Versus Time-to-Exhaustion Tests: Effects on Critical Power, W', and Oxygen-Uptake Kinetics. *Int J Sports Physiol Perform, 13*(2), 183-188. doi:10.1123/ijspp.2016-0761

Karsten, B., Hopker, J., Jobson, S. A., Baker, J., Petrigna, L., Klose, A., & Beedie, C. (2017). Comparison of inter-trial recovery times for the determination of critical power and W' in cycling. *J Sports Sci, 35*(14), 1420-1425. doi:10.1080/02640414.2016.1215500

Karsten, B., Jobson, S. A., Hopker, J., Stevens, L., & Beedie, C. (2015). Validity and reliability of critical power field testing. *Eur J Appl Physiol, 115*(1), 197-204. doi:10.1007/s00421-014-3001-z

Krustrup, P., Soderlund, K., Mohr, M., & Bangsbo, J. (2004). The slow component of oxygen uptake during intense, sub-maximal exercise in man is associated with additional fibre recruitment. *Pflugers Arch, 447*(6), 855-866. doi:10.1007/s00424-003-1203-z

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014). Transference of 3D accelerations during cross country mountain biking. *J Biomech, 47*(8), 1829-1837. doi:10.1016/j.jbiomech.2014.03.024

Macdermid, P. W., & Morton, R. H. (2012). A longitudinal analysis of start position and the outcome of World Cup cross-country mountain bike racing. *J Sports Sci, 30*(2), 175-182. doi:10.1080/02640414.2011.627368

Macdermid, P. W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. *J Sports Sci, 30*(14), 1491-1501. doi:10.1080/02640414.2012.711487

Maier, T., Schmid, L., Muller, B., Steiner, T., & Wehrlin, J. P. (2017). Accuracy of Cycling Power Meters against a Mathematical Model of Treadmill Cycling. *Int J Sports Med, 38*(6), 456-461. doi:10.1055/s-0043-102945

Martin, L., Lambeth-Mansell, A., Beretta-Azevedo, L., Holmes, L. A., Wright, R., & St Clair Gibson, A. (2012). Even between-lap pacing despite high within-lap variation during mountain biking. *Int J Sports Physiol Perform, 7*(3), 261-270. doi:10.1123/ijspp.7.3.261

Maturana, F. M., Keir, D. A., McLay, K. M., & Murias, J. M. (2017). Critical power testing or self-selected cycling: Which one is the best predictor of maximal metabolic steady-state? *Journal of Science and Medicine in Sport, 20*(8), 795-799.

Michael, S., Hoon, M., Areta, J., Patton, R., & Chapman, P. (2017). Accuracy, precision and test-retest reproducibility of the Wahoo KICKR cycling trainer. *Journal of Science and Medicine in Sport, 20*, e115.

Miller, M. C., Fink, P. W., Macdermid, P. W., Allen, D., & Stannard, S. R. (2018). Braking and performance characteristics of experienced and inexperienced mountain bikers navigating an isolated off-road turn using a brake power meter. *International Journal of Performance Analysis in Sport, 18*(4), 495-506. doi:10.1080/24748668.2018.1496383

Miller, M. C., Fink, P. W., Macdermid, P. W., & Stannard, S. R. (2019). Quantification of brake data acquired with a brake power meter during simulated cross-country mountain bike racing. *Sports Biomech, 18*(4), 343-353. doi:10.1080/14763141.2017.1409257

Miller, M. C., & Macdermid, P. W. (2015). Predictive Validity of Critical Power, The Onset of Blood Lactate and Anaerobic Capacity for Cross-Country Mountain Bike Race Performance. *Sports and Exercise Medicine Open Journal, 1*(4), 105-110. doi:10.17140/semoj-1-118

Miller, M. C., Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2016). Agreement between Powertap, Quarq and Stages power meters for cross-country mountain biking. *Sports Technology, 8*(1-2), 44-50. doi:10.1080/19346182.2015.1108979

Miller, M. C., Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2017). Performance and physiological effects of different descending strategies for cross-country mountain biking. *Eur J Sport Sci, 17*(3), 279-285. doi:10.1080/17461391.2016.1237550

Miller, M. C., Moir, G. L., & Stannard, S. R. (2014). Validity of using functional threshold power and intermittent power to predict cross-country mountain bike race outcome. *Journal of Science and Cycling, 3*(1), 16-20.

Miura, A., Sato, H., Sato, H., Whipp, B. J., & Fukuba, Y. (2000). The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics, 43*(1), 133-141. doi:10.1080/001401300184693

Monod, H., & Scherrer, J. (2007). The Work Capacity of a Synergic Muscular Group. *Ergonomics, 8*(3), 329-338. doi:10.1080/00140136508930810

Morton, R. H. (2006). The critical power and related whole-body bioenergetic models. *Eur J Appl Physiol, 96*(4), 339-354. doi:10.1007/s00421-005-0088-2

Morton, R. H., & Billat, L. V. (2004). The critical power model for intermittent exercise. *Eur J Appl Physiol, 91*(2-3), 303-307. doi:10.1007/s00421-003-0987-z

Muniz-Pumares, D., Karsten, B., Triska, C., & Glaister, M. (2019). Methodological Approaches and Related Challenges Associated With the Determination of Critical Power and Curvature Constant. *J Strength Cond Res, 33*(2), 584-596. doi:10.1519/JSC.0000000000002977

Nikitakis, I. S., Paradisis, G. P., Bogdanis, G. C., & Toubekis, A. G. (2019). Physiological Responses of Continuous and Intermittent Swimming at Critical Speed and Maximum Lactate Steady State in Children and Adolescent Swimmers. *Sports (Basel), 7*(1), 25-25. doi:10.3390/sports7010025

Nimmerichter, A., Novak, N., Triska, C., Prinz, B., & Breese, B. C. (2017). Validity of Treadmill-Derived Critical Speed on Predicting 5000-Meter Track-Running Performance. *J Strength Cond Res, 31*(3), 706-714. doi:10.1519/JSC.0000000000001529

Nimmerichter, A., Prinz, B., Gumpenberger, M., Heider, S., & Wirth, K. (2020). Field-Derived Power-Duration Variables to Predict Cycling Time-Trial Performance. *Int J Sports Physiol Perform*(January), 1-8. doi:10.1123/ijspp.2019-0621

Novak, A. R., Bennett, K. J. M., Fransen, J., & Dascombe, B. J. (2018). A multidimensional approach to performance prediction in Olympic distance cross-country mountain bikers. *J Sports Sci, 36*(1), 71-78. doi:10.1080/02640414.2017.1280611

Pallares, J. G., Moran-Navarro, R., Ortega, J. F., Fernandez-Elias, V. E., & Mora-Rodriguez, R. (2016). Validity and Reliability of Ventilatory and Blood Lactate Thresholds in Well-Trained Cyclists. *PLoS ONE, 11*(9), e0163389. doi:10.1371/journal.pone.0163389

Passfield, L., Hopker, J. G., Jobson, S., Friel, D., & Zabala, M. (2017). Knowledge is power: Issues of measuring training and performance in cycling. *J Sports Sci, 35*(14), 1426-1434. doi:10.1080/02640414.2016.1215504

Pettitt, R. W. (2016). Applying the Critical Speed Concept to Racing Strategy and Interval Training Prescription. *Int J Sports Physiol Perform, 11*(7), 842-847. doi:10.1123/ijspp.2016-0001

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. *Med Sci Sports Exerc, 48*(11), 2320-2334. doi:10.1249/MSS.0000000000000939

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. doi:10.1080/00140138808966766

Pringle, J. S., Doust, J. H., Carter, H., Tolfrey, K., Campbell, I. T., Sakkas, G. K., & 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. *Eur J Appl Physiol, 89*(3-4), 289-300. doi:10.1007/s00421-003-0799-1

Prins, L., Terblanche, E., & Myburgh, K. H. (2007). Field and laboratory correlates of performance in competitive cross-country mountain bikers. *J Sports Sci, 25*(8), 927-935. doi:10.1080/02640410600907938

Rossiter, H. B., Ward, S. A., Howe, F. A., Kowalchuk, J. M., Griffiths, J. R., Whipp, B. J., & Dynamics, B. J. W. (2002). Dynamics of intramuscular 31 P-MRS P. *Interface*, 2059-2069.

Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Med Sci Sports Exerc, 44*(8), 1526-1532. doi:10.1249/MSS.0b013e3182517a80

Skiba, P. F., Fulford, J., Clarke, D. C., Vanhatalo, A., & Jones, A. M. (2015). Intramuscular determinants of the ability to recover work capacity above critical power. *Eur J Appl Physiol, 115*(4), 703-713. doi:10.1007/s00421-014-3050-3

Skiba, P. F., Jackman, S., Clarke, D., Vanhatalo, A., & Jones, A. M. (2014). Effect of work and recovery durations on W' reconstitution during intermittent exercise. *Med Sci Sports Exerc, 46*(7), 1433-1440. doi:10.1249/MSS.0000000000000226

Stapelfeldt, B., Schwirtz, A., Schumacher, Y. O., & Hillebrecht, M. (2004). Workload demands in mountain bike racing. *Int J Sports Med, 25*(4), 294-300. doi:10.1055/s-2004-819937

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Med Sci Sports Exerc, 29*(8), 1104-1108. doi:10.1097/00005768-199708000-00017

Toubekis, A., & Tokmakidis, P. S. (2013). METABOLIC RESPONSES AT VARIOUS INTENSITIES RELATIVE TO CRITICAL SWIMMING VELOCITY. *27*(6), 1731-1741.

Townsend, N. E., Nichols, D. S., Skiba, P. F., Racinais, S., & Periard, J. D. (2017). Prediction of Critical Power and W' in Hypoxia: Application to Work-Balance Modelling. *Front Physiol, 8*(MAR), 180. doi:10.3389/fphys.2017.00180

Triska, C., Karsten, B., Beedie, C., Koller-Zeisler, B., Nimmerichter, A., & Tschan, H. (2018). Different durations within the method of best practice affect the parameters of the speed-duration relationship. *Eur J Sport Sci, 18*(3), 332-340. doi:10.1080/17461391.2017.1418025

Triska, C., Karsten, B., Heidegger, B., Koller-Zeisler, B., Prinz, B., Nimmerichter, A., & Tschan, H. (2017). Reliability of the parameters of the power-duration relationship using maximal effort time-trials under laboratory conditions. *PLoS ONE, 12*(12), e0189776. doi:10.1371/journal.pone.0189776

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: a critical review. *Br J Sports Med, 43*(6), e1. doi:10.1136/bjsm.2009.057562

Vanhatalo, A., Doust, J. H., & Burnley, M. (2007). Determination of critical power using a 3-min all-out cycling test. *Medicine & Science in Sports & Exercise, 39*(3), 548-555.

Vanhatalo, A., Fulford, J., DiMenna, F. J., & Jones, A. M. (2010). Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Exp Physiol, 95*(4), 528-540. doi:10.1113/expphysiol.2009.050500

Vanhatalo, A., & Jones, A. M. (2009). Influence of Creatine Supplementation on the Parameters of the "All-Out Critical Power Test". *Journal of Exercise Science & Fitness, 7*(1), 9-17. doi:10.1016/s1728-869x(09)60002-2

Vanhatalo, A., Jones, A. M., & Burnley, M. (2011). Application of critical power in sport. *Int J Sports Physiol Perform, 6*(1), 128-136. doi:10.1123/ijspp.6.1.128

Vassallo, C., Gray, A., Cummins, C., Murphy, A., & Waldron, M. (2020). Exercise tolerance during flat over-ground intermittent running: modelling the expenditure and reconstitution kinetics of work done above critical power. *Eur J Appl Physiol, 120*(1), 219-230. doi:10.1007/s00421-019-04266-8

Viana, B. F., Pires, F. O., Inoue, A., & Santos, T. M. (2018). Pacing Strategy During Simulated Mountain Bike Racing. *Int J Sports Physiol Perform, 13*(2), 208-213. doi:10.1123/ijspp.2016-0692

Zadow, E. K., Kitic, C. M., Wu, S. S., & Fell, J. W. (2018). Reliability of power settings of the Wahoo KICKR power trainer after 60 hours of use. *International Journal of Sports Physiology and Performance, 13*(1), 119-121.

Zadow, E. K., Kitic, C. M., Wu, S. S., Smith, S. T., & Fell, J. W. (2016). Validity of Power Settings of the Wahoo KICKR Power Trainer. *Int J Sports Physiol Perform, 11*(8), 1115-1117. doi:10.1123/ijspp.2015-0733
Zagatto, A. M., Papoti, M., & Gobatto, C. A. (2008). Anaerobic capacity may not be determined by critical power model in elite table tennis players. *Journal of sports science & medicine, 7*(1), 54.

# 5 Article

**Title:** Understanding the workload demands of Cross-country mountain bike cycling using the Critical Power concept

## *Abstract*


**Objective:** To examine the pacing pattern by describing the continuous workload requirements in relation to critical power (CP) of cross-country mountain bike cycling (XCO-MTB).

**Methods:** Five male and two female nationally competitive XCO-MTB athletes (age: 23 ±4 years, $VO_{2peak}$:71 ± 8.1 mL·kg$^{-1}$·min$^{-1}$) completed an official XCO-MTB race and then performed two lab tests using their own bike mounted on a cycle ergometer with their own power meter. Speed, cadence, power output, and HR were recorded during the XCO-MTB race. $VO_{2peak}$ and maximal aerobic power (MAP) were established, and CP were calculated using three maximum effort time trials of 12, 7 and 3 minutes. PO >CP were divided into three magnitude based zones [P] CP up to 1.5 times CP[P1], 1.5 to 2 times CP[P2], and 2 times and above CP[P3] and five zones based on duration of individual segments with >CP PO.

**Results:** During the XCO-MTB event, average speed and PO was 14.4±1.9km*h $^{-1}$ and 249±63 W, respectively. Average CP was 329±74W and PO varied from 0 to 277±29% of MAP. During the race, 40±8% of race time was spent with PO >CP with mean PO equal to 76±9% of CP. Average percent of lap time spent in P1, P2 and P3 was 25±4 %, 11±6 % and 4±5 %, respectively. Total time >CP and distribution of P2-3 decreased significantly from initial rounds, with no significant changes in P1 or distribution of duration.

**Conclusions:** During this XCO-MTB race, about 40% of race time was spent above the CP, with a reduction of high magnitude >CP actions in P2 and P3 following initial rounds. The observed highly variable pacing pattern in XCO-MTB imply the needs for rapid changes in metabolic power output during races, displaying a prominent number of separate short-lived actions with little lap-to-lap variation in duration.

## *Introduction*

Olympic cross-country mountain biking (XCO-MTB) are off-road cycling events characterized by high intensity mass-start and a varied off-road track structure leading to a high workload variability, demanding continual high intensity and the use of numerous bursts of high power output [PO]  (Granier et al., 2018; Hays, Devys, Bertin, Marquet, & Brisswalter, 2018; Inoue, Sa Filho, Mello, & Santos, 2012; Macdermid & Stannard, 2012). The challenging terrain test contestant's ability to optimally distribute PO across a race, resulting in multiple physiological characteristics being highlighted when attempting to explain what affects performance in the sport (Abbiss & Laursen, 2008; Abbiss et al., 2013; Hays et al., 2018; Impellizzeri, Rampinini, Sassi, Mognoni, & Marcora, 2005b; Macdermid & Stannard, 2012)

Several studies have put forth compelling evidence for the importance of aerobic characteristics for performance, i.e. $VO_{2max}$ (Hays et al., 2018; Impellizzeri & Marcora, 2007), maximal aerobic power output [MAP] (Granier et al., 2018; Hays et al., 2018) and  ventilatory- and lactate thresholds (Impellizzeri, Marcora, Rampinini, Mognoni, & Sassi, 2005a; Miller & Macdermid, 2015; Miller, Moir, & Stannard, 2014; Viana, Pires, Inoue, & Santos, 2018). Moreover, following Inoue et al. (2012) correlating a modified Wingate test to XCO-MTB performance, anaerobic power have also been classified as an important determinant of performance due the intermittent aspect of XCO-MTB. While overarching lap-to-lap pacing and unidimensional performance prediction have been successfully applied to XCO-MTB, the extensive intralap variability is not well accounted for (Gregory, Johns, & Walls, 2007; Impellizzeri et al., 2005a; Inoue et al., 2012; Novak, Bennett, Fransen, & Dascombe, 2018). Besides, many of the laboratory tests are not readily available to coaches and athletes due to the need for advanced equipment and training. Noticing the lack of an ecological testing method, Miller et al. (2015) later proposed Critical power [CP] to be an ecological framework to assess performance in XCO-MTB.

Critical Power is considered to be the highest sustainable rate of oxidative metabolism without a continuous loss of homeostasis, defined as the boundary between steady state and non-steady state exercise (Jones, Wilkerson, DiMenna, Fulford, & Poole, 2008; Poole, Ward, Gardner, & Whipp, 1988). Applying the CP concept to XCO-MTB could delineate workload attributable to aerobic and anaerobic sources during intermittent PO (Chidnok et al., 2012; Hays et al., 2018; Martin et al., 2012).

In intermittent exercise such as XCO-MTB, workload >CP is believed to steadily drain the finite capacity to perform work above CP (labelled W’), and has been demonstrated to include varying degrees of regeneration of W’ dependent on workload during <CP segments (Skiba, Jackman, Clarke, Vanhatalo, & Jones, 2014). Interestingly, recent studies on the pacing of XCO-MTB have displayed a shift in contribution of actions above MAP, suggesting anaerobic actions to develop throughout an event (Granier et al., 2018; Hays et al., 2018). Furthermore, multiple studies have noted that PO may underestimate race intensity, mainly rationalized by the lack of sensitivity to workload intensity in segments without PO (Hays et al., 2018; Hurst et al., 2012; Miller, Macdermid, Fink, & Stannard, 2017). Taken together, while both PO and non-PO intensity affecting the potential >CP capacity, there could potentially be an evolution of PO >CP actions based on the availability of W’ which could reflect the total intensity of the race (Chidnok et al., 2012; Hays et al., 2018). However, this is yet not well investigated in intermittent endurance sports.

Due to CPs sensitivity determine work in both aerobic and anaerobic domains, assessing XCO-MTB race through the use this framework could elucidate how anaerobic capacity is utilized throughout a race and provide a practical test for assessing performance for coaches and athletes in the sport. (Chidnok et al., 2012; Triska et al., 2017). To the best of our knowledge, no studies to date have applied the CP concept to examine PO in an XCO-MTB race. Consequently, the aim of this study was to (1) to assess the workload requirements of XCO-MTB using power output and the critical power concept, (2) to examine characteristics of >CP actions throughout a race. We hypothesized that average power output is close to calculated critical power, and that intensity of actions above critical power to decrease as a function of race time.

# Methods

## Participants

Eight XCO-MTB athletes were recruited for this study (male n=6, female n=2), all competing at a national level in Norway; however, one male was excluded from further analysis due to absence from post-testing. Table 1 displays the subject characteristics for this study. Inclusion criteria were as follows: (1) participation in a specified national XCO-MTB race, (2) access to a portable power meter for use during the race and post-race testing. All participants completed the race. Prior to data collection, each participant gave written informed consent to participate in the study. The protocol was approved by the local ethics committee of the Norwegian School of Sport Sciences and reported to the Norwegian Centre for Research Data.

***Table 1**: Subject anthropometry and characteristics an at baseline (n=7)*

| | **Mean** | **Range** |
|---|---|---|
| Age (yr) | 23 | 19 - 31 |
| Body mass (kg) | 69 | 61 - 88 |
| Height (cm) | 178 | 161 - 198 |
| $VO_{2max}$ ($ml*min^{-1}*kg^{-1}$) | 71 | 59 - 79 |
| $VO_{2max}$ ($L*min^{-1}$) | 4.9 | 3.7 - 6.0 |
| Mean PO 30-sec test (W) | 754 | 448 - 991 |
| MAP (W) | 397 | 267 - 568 |
| CP (W) | 329 | 241 - 456 |

### *General design*

The study consisted of three sessions, participants took part in an official XCO race and reported to the lab on two occasions separated by at least 48 h, the first of which served as familiarisation. The men and women competed in different races, but on the same track, at the same time of day. Participants height and body mass were measured at the start of each lab day, and they completed a short motivation questionnaire pre- and post-testing. All athletes used their own bike and power meter mounted on a cycling ergometer (KICKR, Wahoo Fitness, Atlanta, USA) and controlled using the accompanied app (Wahoo Fitness, 2019, version 5.23.0), the system which were tested and considered to be reliable, as established in earlier studies (Miller, Macdermid, Fink, & Stannard, 2016). Validation data can be found in appendix 1. A virtual gear changer was mounted close to the handlebar where the participants were able to manipulate the resistance of the KICKR (displayed in watts) on self-paced tests. Subjects were instructed to use the power and cadence feedback from their personal cycling computer.

Power and cadence were recorded with their personal power meter and used for further analysis. Participants performed two test days to determine the power-duration relationship, with the first day serving as a familiarization as proposed by Triska et al.

(2017). $VO_2$ data for time trials [TT] were only recorded for the second test day, the days were otherwise identical and is shown in Figure 1.

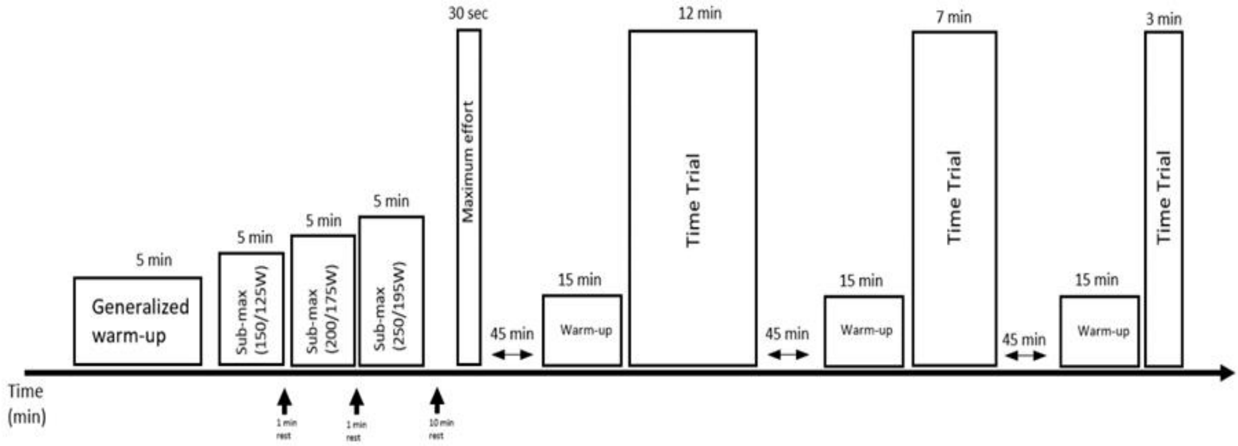



***Figure 1:*** *Illustration of test protocol for submaximal workloads and performance tests conducted on the indoor test days on subjects' personal bike. Three submaximal workloads; 150, 200 and 250W for men and 125, 175, 195 W women, respectively. Followed by performance tests beginning with a 30 seconds all-out test before a 12 min TT, a 7 min TT and a 3 min TT in that order. All performance tests after the maximal effort test were separated by 45 min rest and 15 min warm-up.*

## *Equipment*

Participants used their personal bike, heart rate (HR) monitor, cycling computer and power meter. For the power meters there where two different in use, Quark (N=6) and 4iii (N=1). Oxygen consumption was measured with an automatic ergospirometry system (Oxycon Pro, Jaeger Instrument, Hoechberg, Germany). Participants breathed through a mouthpiece into a two-way valve preventing "rebreathing" (Hans Rudolph 2700 series, Hans Rudolph, Inc., Kansas City, USA). Expired air travelled through a flexible hose to a mixing chamber for analysis whereas volume was measured by a turbine (Triple V volume transducer; Erich Jaeger GmbH, Hoechberg, Tyskland). The oxygen analyser was calibrated prior to each test with a standardized calibration gas (180kPa, 5.55% carbon dioxide (CO2) and 94.45% nitrogen gas (N2)). The airflow turbine (Triple V; Erich Jaeger GmbH, Hoechberg, Germany) was manually calibrated with a three-litre calibration pump (CalibrationSyringe, series 5530; Hans Rudolph Inc., Kansas City, Missouri, USA). In addition, temperature, pressure and humidity were calibrated. Heart rate was recorded with the participants personal HR monitor.

### *Competition testing*

Participants competed in an official regional XCO-MTB race (Karl XII rittet NC10, Norway, UCI cat 1, Rundbane (XCO)), and were to complete the race as they would have otherwise. A single circuit of the track included uphill and downhill sections with a total length of 3.8 km, with 101 m climb and 99 m descent based as reported by race organizers (Figure 2). Round times, PO, HR and speed data were recorded during the race. The number of laps differed between genders, 6 for males and 5 for females. In order to compare data from all participants, we divided the race into following parts: start loop (SL), round 1 (R1), round 2 (R2), round 3(R3), the second to last lap (Ln-1), and final lap (LN), similar to Granier et al. (2018). Efforts exerted above CP were divided into three categories based on magnitude: From CP to 1.5*CP [P1],1.5*CP to 2*CP[P2] and 2*CP and above [P3]. In addition, actions above CP were subdivided into five groups based on duration of >CP actions: 1 -5 s[TS1], 6-10 s[TS2], 11-15 s[TS3], 16-20 s[TS4] and >21 s [TS5]. Data were recorded at a frequency of 1 Hz and transmitted to each participant's personal cycling computer.

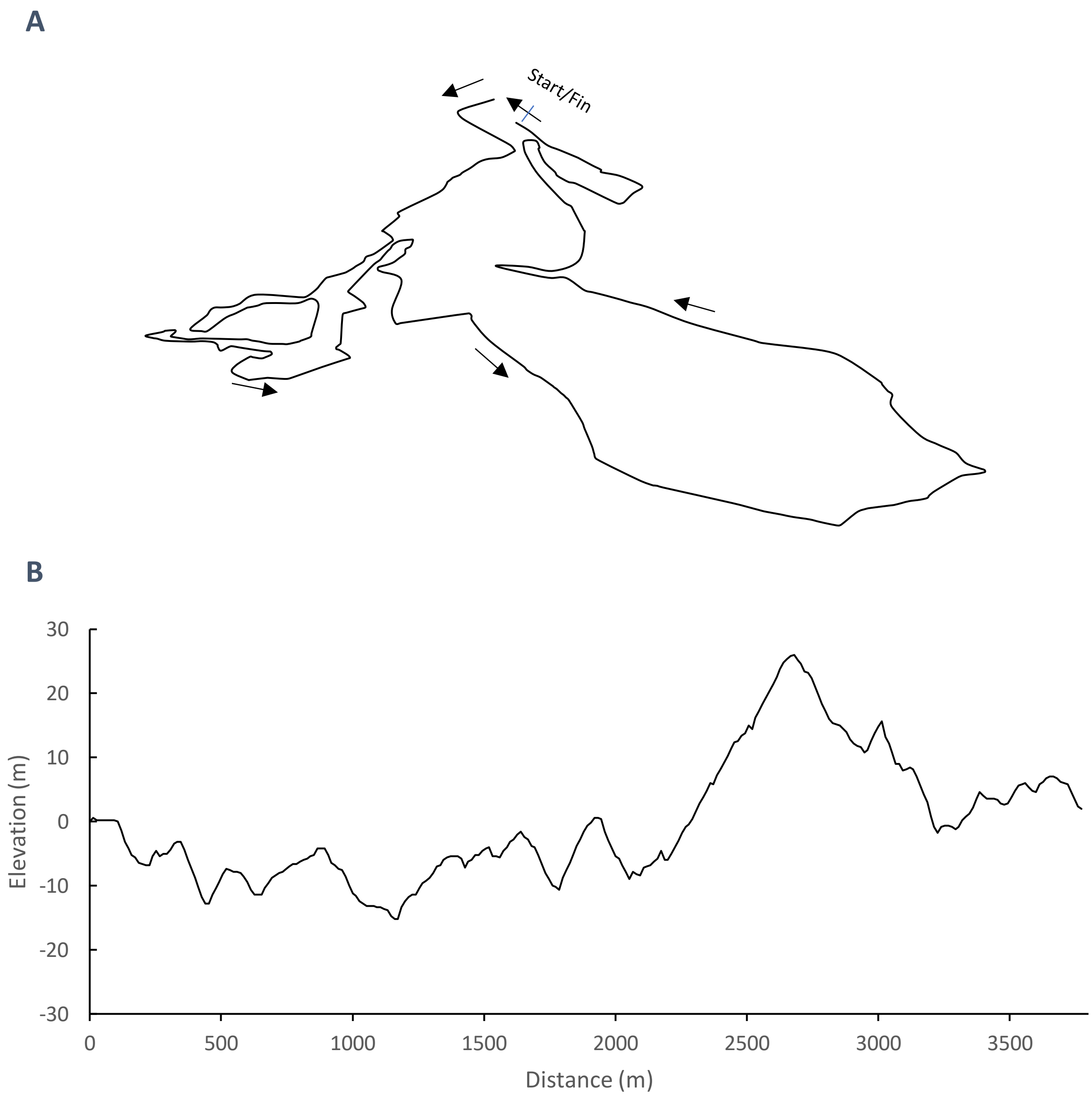



***Figure 2:*** *Graphical presentation of Lap outline and profile (A) topographic illustration of lap path. (B) Elevation change during one lap of the track*

## *Indoor testing*

### Submaximal test

On each test day, each participant completed a 10-minute warm-up (range 50 - 150W) before a submaximal, incremental exercise test to determine individual relationship between external power production and $VO_2$. The test consisted of 5-min steps at work rates 150, 200, and 250 W for men and 125, 175, 195 W for women with 1-minute breaks between each of the work-rates. Participants were free to choose their preferred cadence but were instructed to maintain chosen cadence during all tests. $VO_2$, respiratory exchange ratio, and HR were measured during the last 2.5 min as well as the athletes Rate of perceived exhaustion using Borgs (1970) 6 to 20 scale at the end of each step. The participants were instructed to remain seated and maintain a consistent cadence which would also be used in the TT. The submaximal work rates corresponded to 46 ± 7, 57 ± 10 and 68 ± 10 % of $VO_{2peak}$ achieved during the TT.

External power from the power meter and $VO_2$ were the main assessment measures for the submaximal workloads. Continuous measures during the test was $VO_2$ and HR. Following completion of each workload HR and RPE was immediately recorded.

## Performance tests

Following 10 minutes active rest, a maximal all-out cycling test was performed to determine the maximal power output for each participant. Subjects were asked to perform 30 second all-out effort, starting from a standstill. A 5 second countdown initiated the test and participants were strongly encouraged to accelerate as much as possible and maintain maximal power output. Subjects were instructed to remain seated throughout the test and were free to change the ergometer resistance on the virtual gear changer throughout the test. Following the test they were allowed up to 10 min active recovery before the 45 min rest period to the remaining performance test.

CP and W' were established using three maximum effort time trials of 12[TT12], 7 [TT7] and 3[TT3] minutes in that order, as suggested by Karsten et al. (2017). Before each TT, a 15 min warm-up was completed with light intensity from start to 7 min, followed by medium-high intensity from minute 7 to 10 and finishing with a 5 minutes light intensity from minute 10 to 15. TT's are started from standstill and quickly accelerated up to a work rate the participants predict they could sustain for the length of each TT but were free to adjust the ergometer resistance as in the previous test. Participants were instructed to maintain their previously chosen cadence throughout the TT. Feedback on time left and strong verbal encouragement were provided during the test. After each TT the participant were allowed 10 min active recovery before proceeding to 45 min passive rest. The first indoor day was used as familiarization and $VO_2$ for TT's were therefore only recorded on the second day. To combat a negative pacing strategy, a forced watt was set on the TTs for the second day, locking watt-resistance for 1 min at the beginning of the 12min and 7 min TT, and for 30sec for the 3 min TT. Watt was locked at the mean watt produced on the familiarization day, and subjects were otherwise free to adjust resistance as usual after the lock.

## Maximal aerobic power

$VO_2$ and PO was used to assess work during submaximal workloads from which linear regression was used to extrapolate the power corresponding to Maximal aerobic power [MAP].

## Calculation of CP and the W' parameter

Linear regression was used to find the CP and W' plotting mean effect against the inverse of time using the P =W' [1/t] + CP) model.

Power output measured above CP during the different laps was normalised to CP and divided into three power zones, watt corresponding to CP to 1.5 times CP[P1], 1.5 to 2 times CP[P2], and >2 times CP[P3]. Efforts above CP were divided into 5 categories based on duration: 1–5 s[TS1], 6–10 s[TS2], 11–15 s[TS3], 16–20 s[TS4], and efforts above 21 s[TS5].

### *Data capture*

Post-testing all exercise trials, power output and cadence were downloaded into cycling desktop software Golden Cheetah (Golden Cheetah training software, goldencheetah.org). Data were subsequently exported to Microsoft Office Excel 365 (Microsoft, Redmond, USA) for further analysis.

### *Statistical analysis*

Test data for normality with a Shapiro-Wilk test and by visual inspection. Unless otherwise specified, data are displayed as mean and standard deviation (SD). Between lap differences are displayed as mean ± SD and 95% Confidence Intervals [95% CI]. One-way Repeated ANOVA with Bonferroni correction for multiple comparisons were performed to identify any statistically significant difference between laps using % of time above CP, distribution of CP magnitude, distribution of CP in duration, % of time above MAP, actions above CP, $km*h^{-1}$, CAD and average HR as dependent variables. If the assumption of sphericity had been violated the Greenhouse-Geisser correction has been used. The statistical significance level was set at $p = 0.05$, and analyses were performed in SPSS Statistics (IBM Corp., Armonk, NY).

# Results

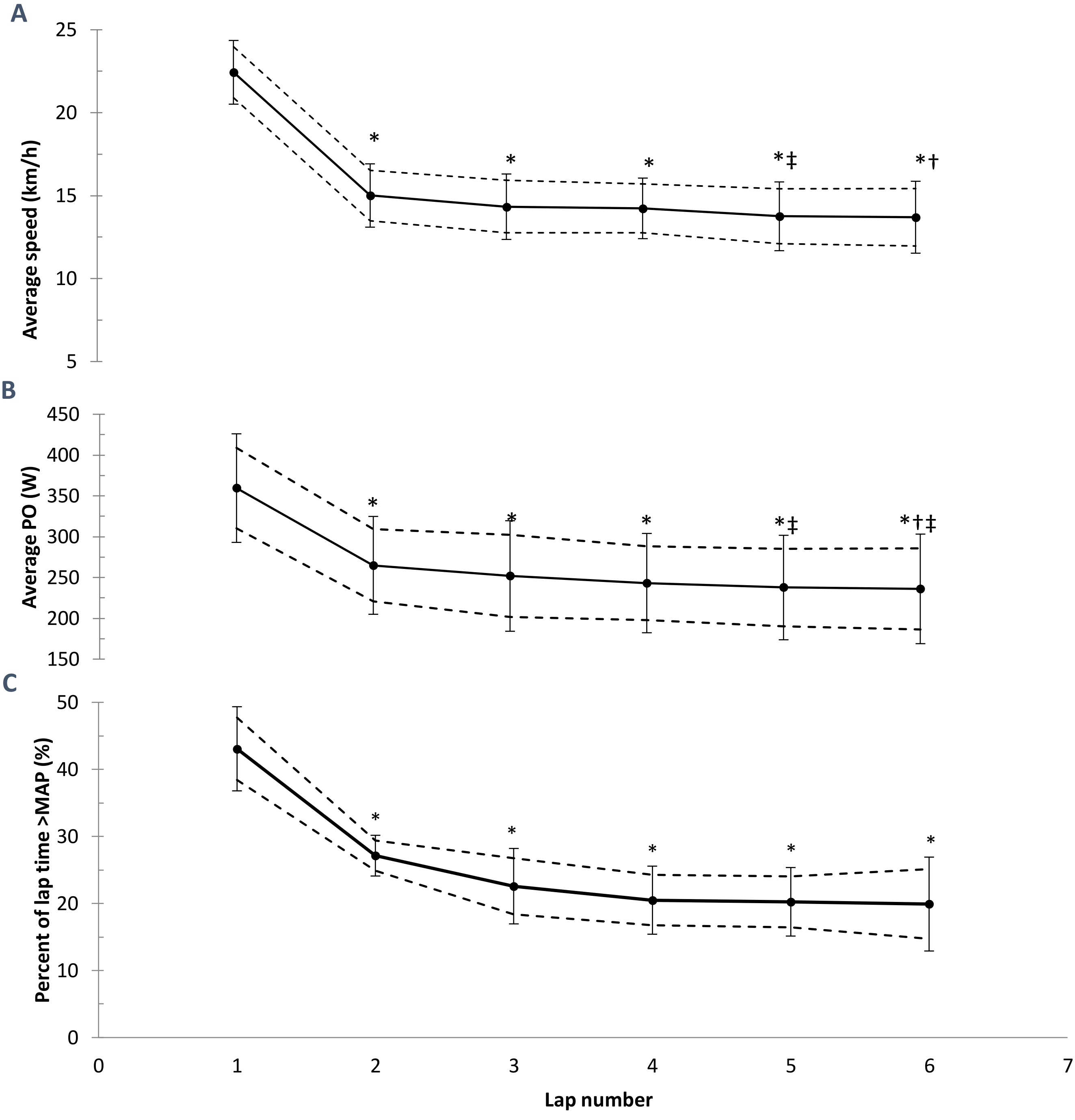



***Figure 3:*** *Lap by lap measurements for (A) Average speed measured for each lap; (B) Average power output; (C) Average percent of lap time above MAP. Data is presented as mean ± SD *different to SL, †different to R1, ‡different to R2. 95% CI are represented by stippled lines*

## *Race characteristics*

A graphical presentation of power output (W) per second (s) for the race is presented in Figure 4, displaying considerable fluctuations in power output throughout the race. Race characteristics are shown in Table 2. Power output averaged over the race duration was

249 ± 63 W, corresponding to 76 ± 9 % of CP and 63 ± 4 % of MAP. Time spent without PO was 20.5 ± 3.1 min or 27 ± 3 % of total race time. PO was highly variable during the race, ranging from 0 to 277 ± 29 % of MAP with a coefficient of variation (CV) of 74.3 ± 2.5 %.

***Table 2**: Race characteristics*

| | **Mean ± SD** | **Range** |
|---|---|---|
| Race duration (min) | 96 | 87 - 107 |
| Avg. lap time (min) | 16 | 14 – 20 |
| Avg. Power output (W) | 249 | 153 - 320 |
| Relative power output ($W*kg^{-1}$) | 3.6 | 2.5 – 4.4 |
| Avg. speed ($km*h^{-1}$) | 14.4 | 9.7 - 18.2 |
| Peak power (W) | 1087 | 692 - 1404 |
| Avg. HR (bpm) | 180 | 170 - 191 |
| Avg. CAD (rpm) | 67 | 59 - 72 |

Abbreviations: km/H, Kilometres per hour; HR, Heart rate; CAD, cadence;

## *Power output and Speed*

Results for round by round mean speed and average power during the race can be seen in Figure 3. There was a significant difference in average speed between laps [F (1,6) = 105, p=<.01] and average power between laps [F (1.708,85.823) = 86, p=<.01], with a significant decrease comparing subsequent laps to SL (Figure 3A,B). Speed was also saw significant change between R1 and LN(p=0.017), as well as R2 and Ln-1(p=0.035), with a mean decrease to the latter round of 9 ± 4 % and 4 ± 2%(Figure 3A). Furthermore, average PO in LN decreased significantly compared to R1(p=0.024) and R2 (p=0.018), and comparing Ln-1 to R2 (p=0.033) (Figure 3B).

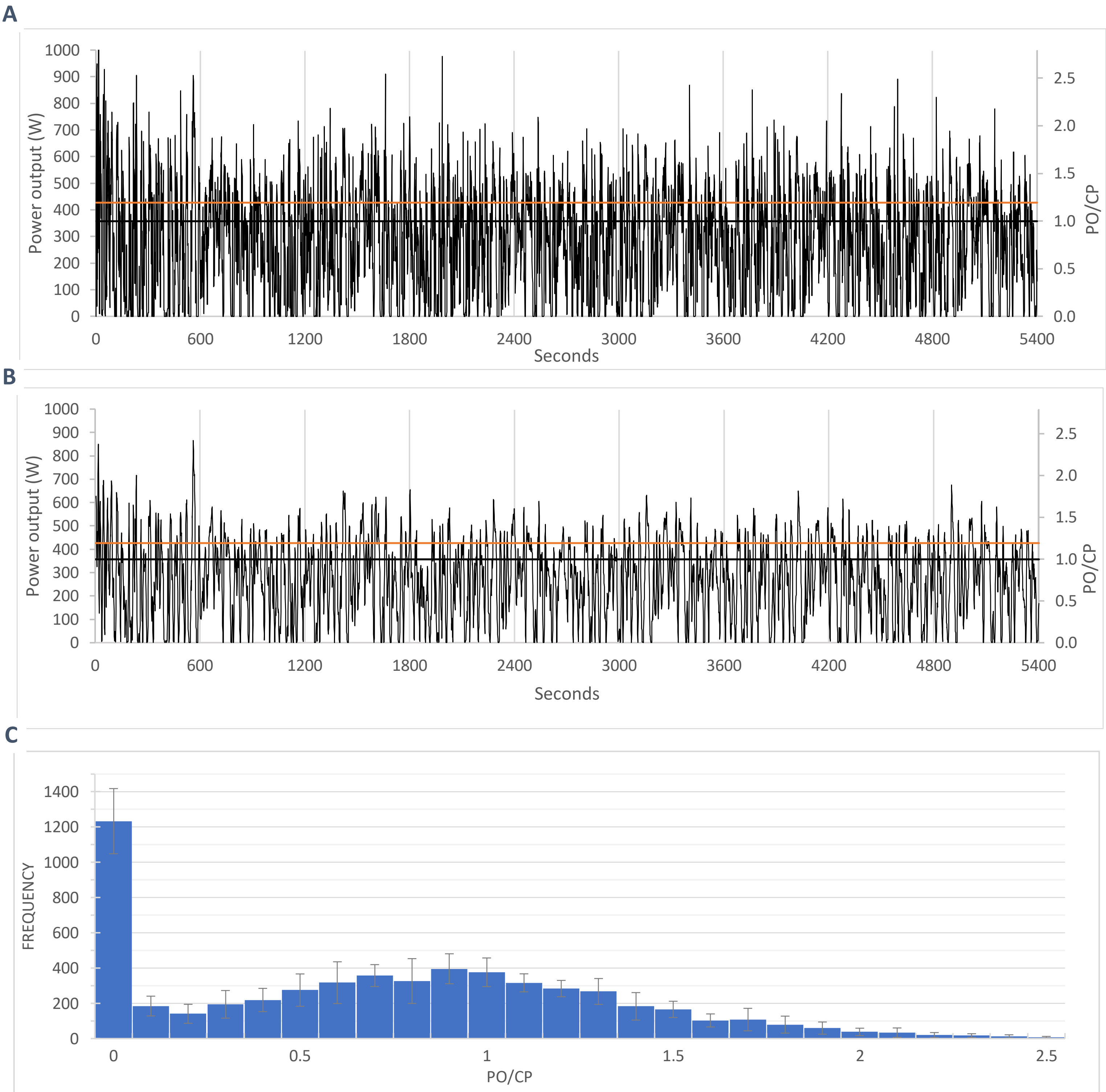



***Figure 4***: *Presentation of power output from the XCO MTB race (A) –Example raw power output from a participant in watts on primary axis and as part of CP on the secondary axis. Orange line represents maximal aerobic power [MAP]- Black line represents CP. B) – Example of recorded power output with 5 second smoothing with power output on the primary axis and proportion of CP on the secondary axis. Orange line represents maximal aerobic power [MAP]- Black line represents CP. (C) Frequency of power output actions normalized to CP throughout the race for all participants, showing extensive frequency of periods without any recorded PO.  reported with SD. Orange line represents maximal aerobic power [MAP]- Black line represents CP.*

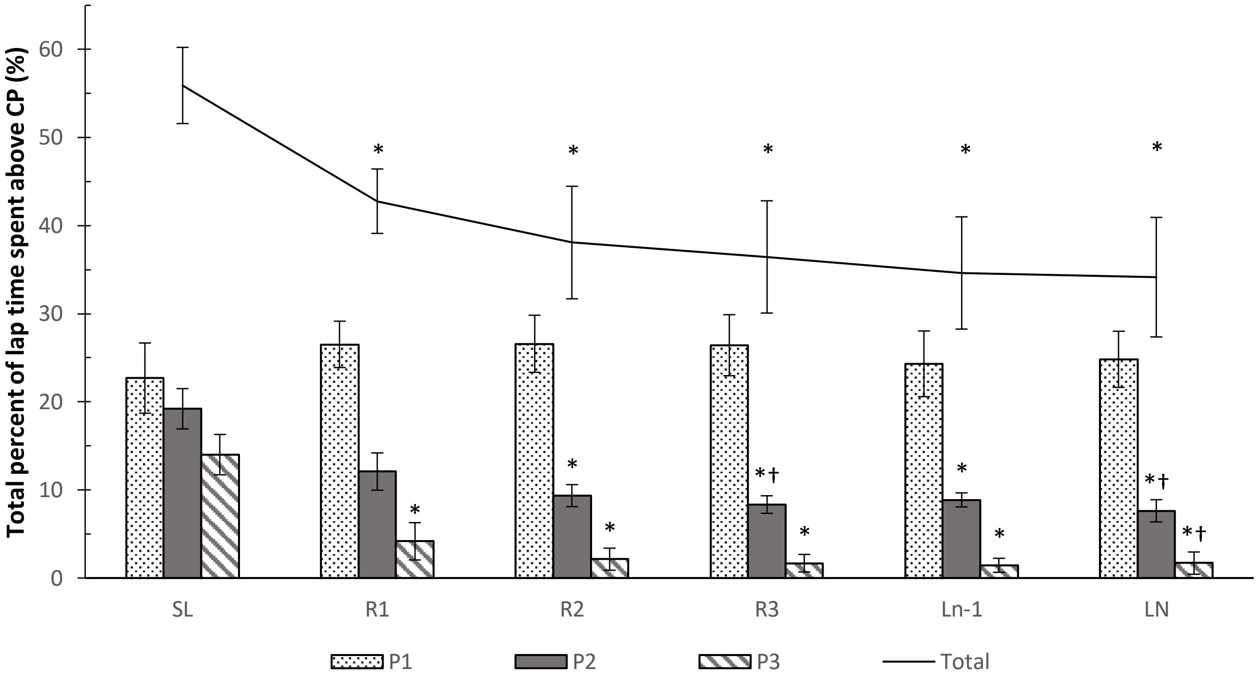



***Figure 5***: *Lap by lap measurements for percentage of lap time spent >CP(Line) and the distribution of >CP actions in % of lap time(columns). P1 are from CP to 1.5 *CP, P2 are from 1.5 to 2*CP, P3 are 2*CP and above. Data is presented as mean ± SD *difference with SL †difference with R1.*

## Race and Critical Power

Average calculated CP were 329 ± 74 W, corresponding to 84 ± 8 % of MAP (Table 1). Percent of race time spent >CP and >MAP was 40.3 ± 7.5 % and 25.6 ± 8.2 %, respectively. Number of actions above CP are presented in Table 3.

Lap by lap comparison of actions above CP in percent of lap time and magnitude distribution are presented in Figure 5. Significant changes between laps was found in actions above CP [F (5,30) = 25.723, p=<0.01] with a reduction in R1 (p=<0.012), R2 (p=0.030), R3 (p=0.011), ln-1 (p=0.015) and LN(p=0.013) compared to SL. >MAP was different between laps [F (1.505,9.032) = 35.462, p=<.01], there was a tendency of reduction from R1 to R3(p=0.071) and Ln-1(p=.100).

Average percent of lap time spent in P1, P2 and P3 was 25 ± 4 %, 11 ± 6 % and 4 ± 5 %, respectively. There were significant differences between laps for P2 [F (1.438,8.626) = 24,793, p=<.01] and P3 [F (1.753,10.521) = 99.773, p=<.01], the same was not found for P1 [F (5,30) = 1.423, p=.244]. P2 displayed a significant difference comparing SL to R2(p=0.034), R3 (p=0.016), Ln-1 (p=0.030) and LN (p=0.026), and R1 compared to R3 (p=0.012) and LN (p=<0.016). P3 displayed a significant difference comparing R1 to LN (p=0.041), and comparing SL to R1, R2, R3, Ln-1 and LN (all p=<0.01)

Throughout the race, >CP output was on average 16.4 ± 2.7 % in TS1, 10.8 ± 4.7 % in TS2, 6.1 ± 6.1 % in TS3, 2 ± 3 % in TS4 and lastly, 2.9 ± 2.8 % in TS5. Repeat measures for significant effects revealed differences in the TS2 [F (2.439,14.633) = 8.131, p=<0.013], TS3 [F (1.347,8.080) = 9.666, p=0.011] and TS5 [F (5,30) = 4.755, p=0.026] , whereas no significant differences were detected in TS1[F (5,30) = 2.343, p=0.066] or TS4 [F (5,30) = 1.064, p=0.360]. A significant effect was observed in TS5 comparing R2 to SL(p=0.021) and Ln-1(p=0.027).

***Table 3**: Number of actions above CP in 5 second segments. Data is presented as mean ± SD*

| | 1 to 5 | 6 to 10 | 11 to 15 | 16 to 20 | 21+ |
|---|---|---|---|---|---|
| SL | 12 ± 3 | 3 ± 1 | 2 ± 1 | 0 ± 0 | 0 ± 0 |
| R1 | 70 ± 13 | 15 ± 2 | 5 ± 2 | 1 ± 1 | 0 ± 1 |
| R2 | 71 ± 13 | 12 ± 2 | 3 ± 3 | 1 ± 1 | 1 ± 1 |
| R3 | 73 ± 13 | 13 ± 5 | 2 ± 2 | 1 ± 1 | 0 ± 1 |
| Ln-1 | 72 ± 10 | 12 ± 4 | 3 ± 2 | 1 ± 1 | 0 ± 0 |
| LN | 72 ± 13 | 11 ± 3 | 2 ± 2 | 1 ± 1 | 0 ± 1 |

## Distribution of above CP actions

Distribution of the magnitude of actions above CP in percent of total actions above CP are presented in Figure 6A. Distribution by magnitude saw significant effects for P1 [F (1.591,9.544) = 71.278, p=<.01], P2 [F (1.574,642.111) = 7.724, p=0.013] and P3 [F (5,30) = 92.530, p=<.01]. Post-hoc revealed a significant increase in time spent in P1 and decrease in exertions in P3 from SL to later rounds (Figure 4). Furthermore, R1 showed significant lap by lap effects in all magnitude distributions: vs R3 (p=<.01), Ln-1 (p=<0.012) and LN (p=<.01) in P1, vs R3 (p=0.015) in P2, and vs LN(p=0.038) in P3.

Distribution of actions above CP subdivided by time segments are presented in Figure 6B. Significant changes between laps was found in TS1 [F (5,30) = 10.256, p=<.01], TS3 [F (1.878,11.271) = 6.546, p=0.014] and TS5 [F (5,30) = 4.716, p=<0.013], however, the same was change was not seen in TS2 [F (2.672,16.031) = 0.678, p=0.562] and TS4 [F (5,30) = 0.591, p=0.707]. Post-hoc revealed significant difference comparing SL to R2 in TS1(p=0.016) and TS5 (p=<0.01).

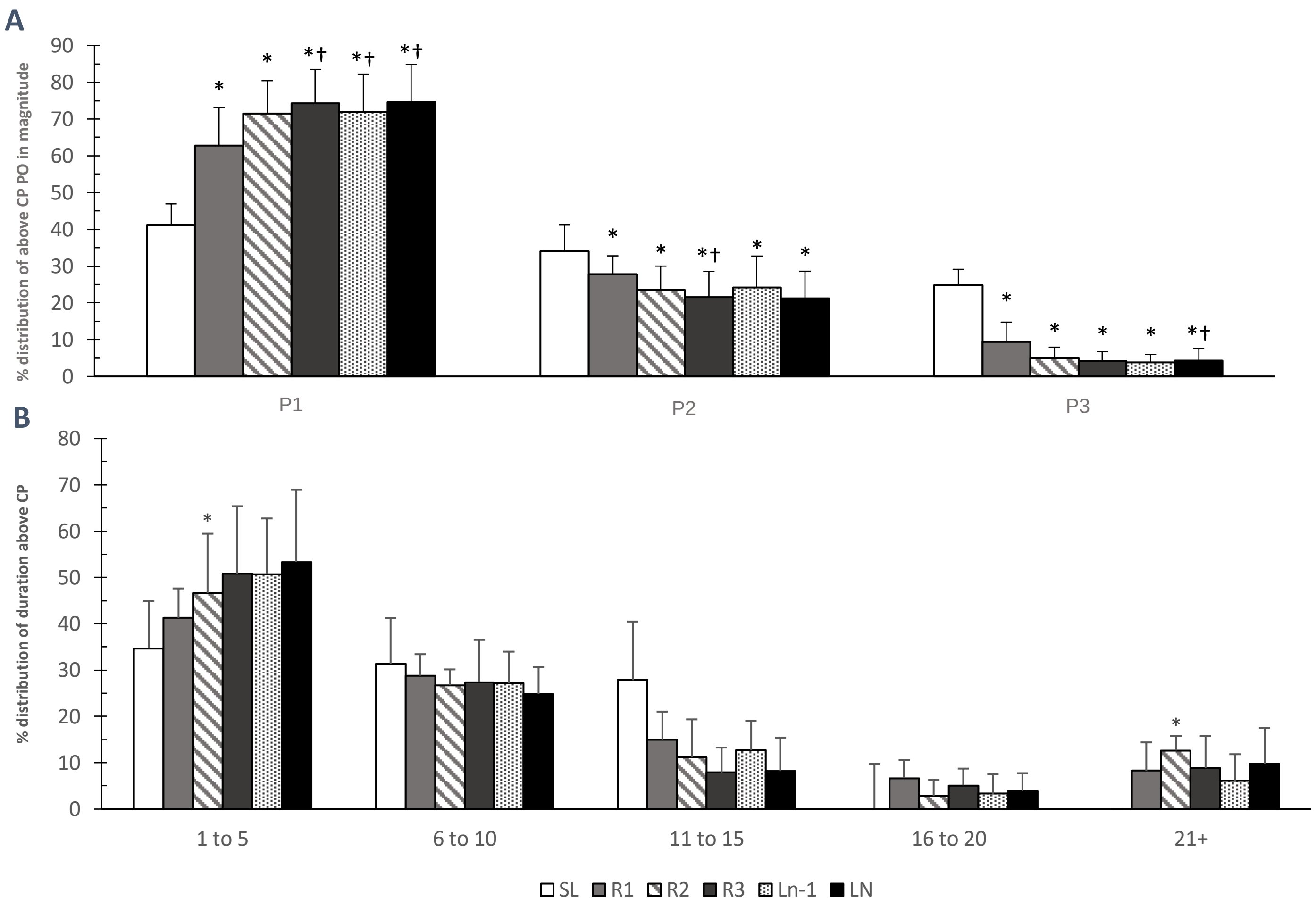



***Figure 6:*** *(A) Percentage of time spent >CP by magnitude distribution, P1 are from CP to 1.5 *CP, P2 are from 1.5 to 2*CP, P3 are 2*CP and above. (B) Percentage of time spent >CP by 5 s segments. Data is presented as mean ± SD *difference with SL †difference with R1 ‡Difference with R2.*

# Discussion

The present study investigated pacing pattern and workload requirements of the current XCO-MTB format using power output and the critical power concept and examine characteristics of >CP actions throughout a race. The main findings from this study:

I. About 40 % of race time was spent above the CP, with a reduction of high magnitude >CP actions in later laps.

II. Power output in P1 did not change notably, and therefore contributed more to >CP PO in later laps.

III. Frequency of actions and duration of >CP did not change significantly over the race, implying track characteristics as central in high intensity PO actions. However, >CP PO tended to become shorter in duration and lower in magnitude throughout the race, suggesting a higher reliance on lower intensity >CP PO.

Overarching lap-to-lap changes have been widely applied to analysis of pacing and workload in XCO-MTB (Granier et al., 2018; Martin et al., 2012; Viana et al., 2018). We observed a higher speed and PO during initial laps, SL and R1, followed by a less decrease in both parameters to subsequent laps. in coherence with earlier studies on speed and PO of XCO-MTB races (**FIGURE 3A, B)** (Abbiss et al., 2013; Granier et al., 2018; Viana et al., 2018). The general perception is that an even-pacing is the optimal strategy for cycling endurance competition with duration above 2 min (Abbiss & Laursen, 2008; Abbiss et al., 2013; Granier et al., 2018; Macdermid & Stannard, 2012; Swain, 1997), while positive pacing is apparent in multiple studies on XCO-MTB (Abbiss et al., 2013; Granier et al., 2018; Martin et al., 2012). We interpret the relatively major decreases in PO in initial rounds and the minor reductions between later laps until race end is related to the nature of the race format supported by earlier findings by Granier et al. (2018). This strengthens the perception of a tendency for an even pacing after the mass-start (Abbiss et al., 2013; Granier et al., 2018; Martin et al., 2012). However, this is expressed as variable pacing within each lap in response to varying external conditions (Abbiss & Laursen, 2008; Martin et al., 2012; Swain, 1997), which begets the need for understanding how even-pacing is maintained where differing terrain are an integral part of workload requirements.

To the best of our knowledge, this is the first study examining PO in XCO-MTB using the CP concept. This assessment revealed a large amount of PO occur >CP during all laps **(FIGURE 4 A,B,C; Figure 5),** with percentage of lap time spent >CP PO during each lap decreasing alongside average PO **(FIGURE 3B; Figure 5)**. However, >CP PO decreased to a slightly lesser extent than average PO R1 vs SL (-22 % vs -36 %), but with negligible differences in decline from R1 to LN (-8.5% vs 8.8%). The progressive decrease was also evident in >MAP PO in percent of lap time**(FIGURE 3C)**, PO associated with MAP being between P1 and P2, showing similarity to previous studies (Granier et al., 2018; Hays et al., 2018). These findings exemplify the high intensity start followed by a more even pacing as reported earlier (Abbiss et al., 2013; Granier et al., 2018; Viana et al., 2018).

A probable explanation for the dissimilar decrease is the noticeable drop in high powered >CP PO in relation to lap time, P2 and P3 being significantly lower in LN compared to SL and R1, with no apparent differences in percent of lap time spent at P1**(FIGURE 5).** Progressive fatigue development could explain the gradual shift towards less intensive PO relative to CP, resisting accumulation of metabolites which could be detrimental to performance (Chidnok et al., 2013; Davies et al., 2017; Hays et al., 2018). Likewise, to reduce uncertainty regarding time left, limiting the strain on anaerobic capacity allow for more flexibility to avoid early exhaustion and termination of exercise (Abbiss & Laursen, 2008; Tucker & Noakes, 2009). It is also quite possible that the positive pacing observed in CP parameters is simply a response to the reduced density of riders after the mass-start, restricting use of high intensity >CP PO to whenever required (Granier et al., 2018). XCO-MTB athletes are certainly encouraged to employ an aggressive start in order to best position themselves relative to other competitors, and further maintain an early advantage to allow for easier optimization of performance without the hindrance of other athletes (Granier et al., 2018). Moreover, the role of decision-making for performance  suggests that removing the stressor of other competitors could potentially allow for more optimized descents (Miller et al., 2017; Novak et al., 2018), limiting work lost to braking and reacceleration (Miller, Fink, Macdermid, Allen, & Stannard, 2018; Miller, Fink, Macdermid, & Stannard, 2019). The recent discoveries surrounding energy expenditure in XCO-MTB not apparent in PO highlights a shortage of information of the workload when PO are the main determinant, likely underestimating total workload (Hays et al., 2018; Hurst et al., 2012; Macdermid, Fink, & Stannard, 2014; Miller et al., 2018; Miller et al., 2017). Thus, this could explain why the average PO is further away from estimated CP than hypothesized.

Interestingly, the decrease in factors associated with PO did not result in any notable change in total actions >CP **(TABLE 3).** Indeed, XCO-MTB clearly exhibits intermittent characteristics through the prominent number of separate short-lived high PO efforts along with the high CV PO observed in this study, as also shown by Hays et al. (2018). However, minor changes in the distribution of >CP PO durations and total actions above >CP suggest high PO actions are a result of challenges presented by the track, exerting high intensity PO actions for a longer duration in response to terrain **(FIGURE 6B).** Moreover, from R2 to subsequent rounds we observed trivial changes in contribution of PO >CP in P1-3 for all durations, showing little lap-to-lap variation inn high intensity PO **(FIGURE 6A)**. This is in support of Martin et al. (2012) conclusions of a spontaneous relationship between pacing and terrain, with even lap-to-lap pacing despite high intralap variability. Conversely, the notably higher PO and speed in R1 compared to LN is accompanied more exertions in P1 (74 % vs 63%) and TS1 (53% vs 41%) **(FIGURE 6 A, B)**. Our results indicate that athletes attempt to maintain even-pacing throughout the event, but utilize >CP PO in P2 and P3 more during SL and R1 than subsequent rounds.

Further investigations should aim to better elucidate lap-to-lap and intra-lap evolution of pacing by clarifying how elements of fatigue and pacing alter tactics in steep uphill or technical downhill segments over multiple laps. Similar to XCO-MTB, cross-country skiing display fluctuations of high intensity periods due to varying terrain (Haugnes, Kocbach, Luchsinger, Ettema, & Sandbakk, 2019), and a disconnect between intensity and speed between terrains have recently been proposed (Karlsson, Gilgien, Gloersen, Rud, & Losnegard, 2018). Suggesting analysis of pacing purely from inter-lap variations in PO could be insufficient for describing the extent of physiological workload in sports with substantial variability in track demands (Karlsson et al., 2018; Martin et al., 2012), and could therefore lead to misinterpretations of intensity (Hays et al., 2018). Analysing workload distribution using CP could gauge severity of workload intensity, translating to higher utilization of high magnitude >CP PO when overall workload are less intensive (Chidnok et al., 2012; Chidnok et al., 2013). Nevertheless, our results indicate that CP could provide a practical and informative view into distribution of PO in XCO-MTB competition and is a novel topic for future research.

**Methodological considerations**

This study examined a race already a part of the participants competitive schedule and we therefore assume participants complete the race as planned, aptly motivated. This could increase the validity of the study. There were a limited number of potential participants in the study resulting in heterogeneity of the recruited group, which might have resulted in a broader range of values for PO, speed and CP parameters (Impellizzeri et al., 2005b).

To increase generalisability to PO from the field, participants performed indoor tests on the bike and power meter they used during the race attached to a reliable cycle ergometer. While this may limit the potential direct comparison between athletes, we believe it could eliminate some of the error associated with using multiple power meters for field data compared to a standardized indoor ergometer. Furthermore, the method for calculating CP have been validated for field-testing, are easy to complete with a timer and power meter and may therefore be of more use for coaches and athletes (Karsten, Jobson, Hopker, Stevens, & Beedie, 2015). While the method has been reported to be reliable and valid, the effects of randomising the order of time trials have not been evaluated and should therefore not be excluded as a potential factor in the calculation. The method has displayed large variations in W' and therefore cannot be applied to the race to examine reconstitution of W', it was not explored further in this study.

Difference between genders on the XCO-MTB format have not been elucidated and can therefore not be excluded as a potential limitation, although one study has reported similar characteristics in performance prediction for male and female XCO-MTB riders (Ahrend, Schneeweiss, Niess, Martus, & Krauss, 2015)

**Practical applications**

Athletes in XCO-MTB perform with several high intensity efforts over the race duration, while the use of PO data is prevalent, practical tools to analyse performance are limited. Interestingly, average PO in XCO-MTB have been stated to approach the intensity which elicit the onset of blood lactate accumulation (Hays et al., 2018; Impellizzeri et al., 2005b; Viana et al., 2018), which reportedly takes place at a similar, albeit lower, PO vs CP (Miller & Macdermid, 2015). Consequently, the ability to use CP could allow for a more practical method to analyse the fluctuating workload during competition (Klitzke Borszcz, Ferreira Tramontin, & Pereira Costa, 2019; Triska et al., 2018; Triska et al., 2017). Understanding high intensity segments in the sport could lead to a more fitting training direction (Hays et al., 2018), guiding future training efforts based on perceived workload and workload derived from CP.

**Conclusion**

Our results show that an XCO-MTB race elicit frequent work performed above the CP and MAP throughout the race, alongside a significant decrease in very high intensity >CP PO following SL and R1 resulting in positive pacing. The observed highly variable pacing pattern in XCO-MTB imply the needs for rapid changes in metabolic power output during races, displaying a prominent number of separate short-lived actions with little lap-to-lap variation in duration.

## References


Abbiss, C. R., & Laursen, P. B. (2008). Describing and understanding pacing strategies during athletic competition. *Sports Med, 38*(3), 239-252. doi:10.2165/00007256-200838030-00004

Abbiss, C. R., Ross, M. L., Garvican, L. A., Ross, N., Pottgiesser, T., Gregory, J., & Martin, D. T. (2013). The distribution of pace adopted by cyclists during a cross-country mountain bike World Championships. *J Sports Sci, 31*(7), 787-794. doi:10.1080/02640414.2012.751118

Ahrend, M., Schneeweiss, P., Niess, A., Martus, P., & Krauss, I. (2015). Prediction of Mountain Bike Race Performance in Female Cyclists (1/2).

Chidnok, W., Dimenna, F. J., Bailey, S. J., Vanhatalo, A., Morton, R. H., Wilkerson, D. P., & Jones, A. M. (2012). Exercise tolerance in intermittent cycling: application of the critical power concept. *Med Sci Sports Exerc, 44*(5), 966-976. doi:10.1249/MSS.0b013e31823ea28a

Chidnok, W., DiMenna, F. J., Fulford, J., Bailey, S. J., Skiba, P. F., Vanhatalo, A., & Jones, A. M. (2013). Muscle metabolic responses during high-intensity intermittent exercise measured by (31)P-MRS: relationship to the critical power concept. *Am J Physiol Regul Integr Comp Physiol, 305*(9), R1085-1092. doi:10.1152/ajpregu.00406.2013

Davies, M. J., Benson, A. P., Cannon, D. T., Marwood, S., Kemp, G. J., Rossiter, H. B., & Ferguson, C. (2017). Dissociating external power from intramuscular exercise intensity during intermittent bilateral knee-extension in humans. *J Physiol, 595*(21), 6673-6686. doi:10.1113/JP274589

Granier, C., Abbiss, C. R., Aubry, A., Vauchez, Y., Dorel, S., Hausswirth, C., & Le Meur, Y. (2018). Power Output and Pacing During International Cross-Country Mountain Bike Cycling. *Int J Sports Physiol Perform, 13*(9), 1243-1249. doi:10.1123/ijspp.2017-0516

Gregory, J., Johns, D. P., & Walls, J. T. (2007). Relative vs. absolute physiological measures as predictors of mountain bike cross-country race performance. *J Strength Cond Res, 21*(1), 17-22. doi:10.1519/00124278-200702000-00004

Haugnes, P., Kocbach, J., Luchsinger, H., Ettema, G., & Sandbakk, O. (2019). The Interval-Based Physiological and Mechanical Demands of Cross-Country Ski Training. *Int J Sports Physiol Perform, 14*(10), 1-7. doi:10.1123/ijspp.2018-1007

Hays, A., Devys, S., Bertin, D., Marquet, L. A., & Brisswalter, J. (2018). Understanding the Physiological Requirements of the Mountain Bike Cross-Country Olympic Race Format. *Front Physiol, 9*(AUG), 1062. doi:10.3389/fphys.2018.01062

Hurst, H., Hurst, H. T., Swarén, M., Hébert-Losier, K., Ericsson, F., Sinclair, J., . . . Holmberg, H.-C. (2012). Influence of course type on upper body muscle activity in elite Cross-Country and Downhill mountain bikers during off Road Downhill Cycling. *Journal of Science and Cycling, 1*(2), 2-9. doi:10.28985/jsc.v1i2.20

Impellizzeri, F. M., & Marcora, S. M. (2007). The physiology of mountain biking. *Sports Med, 37*(1), 59-71. doi:10.2165/00007256-200737010-00005

Impellizzeri, F. M., Marcora, S. M., Rampinini, E., Mognoni, P., & Sassi, A. (2005a). Correlations between physiological variables and performance in high level cross country off road cyclists. *Br J Sports Med, 39*(10), 747-751. doi:10.1136/bjsm.2004.017236

Impellizzeri, F. M., Rampinini, E., Sassi, A., Mognoni, P., & Marcora, S. (2005b). Physiological correlates to off-road cycling performance. *J Sports Sci, 23*(1), 41-47. doi:10.1080/02640410410001730061

Inoue, A., Sa Filho, A. S., Mello, F. C., & Santos, T. M. (2012). Relationship between anaerobic cycling tests and mountain bike cross-country performance. *J Strength Cond Res, 26*(6), 1589-1593. doi:10.1519/JSC.0b013e318234eb89

Jones, A. M., Wilkerson, D. P., DiMenna, F., Fulford, J., & Poole, D. C. (2008). Muscle metabolic responses to exercise above and below the "critical power" assessed using 31P-MRS. *Am J Physiol Regul Integr Comp Physiol, 294*(2), R585-593. doi:10.1152/ajpregu.00731.2007

Karlsson, O., Gilgien, M., Gloersen, O. N., Rud, B., & Losnegard, T. (2018). Exercise Intensity During Cross-Country Skiing Described by Oxygen Demands in Flat and Uphill Terrain. *Front Physiol, 9*(JUL), 846. doi:10.3389/fphys.2018.00846

Karsten, B., Hopker, J., Jobson, S. A., Baker, J., Petrigna, L., Klose, A., & Beedie, C. (2017). Comparison of inter-trial recovery times for the determination of critical power and W' in cycling. *J Sports Sci, 35*(14), 1420-1425. doi:10.1080/02640414.2016.1215500

Karsten, B., Jobson, S. A., Hopker, J., Stevens, L., & Beedie, C. (2015). Validity and reliability of critical power field testing. Eur J Appl Physiol, 115(1), 197-204 Doi:10.1007/s00421-014-3001-z

Klitzke Borszcz, F., Ferreira Tramontin, A., & Pereira Costa, V. (2019). Is the Functional Threshold Power Interchangeable With the Maximal Lactate Steady State in Trained Cyclists? *Int J Sports Physiol Perform, 14*(8), 1029-1035. doi:10.1123/ijspp.2018-0572

Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2014). Transference of 3D accelerations during cross country mountain biking. *J Biomech, 47*(8), 1829-1837. doi:10.1016/j.jbiomech.2014.03.024

Macdermid, P. W., & Stannard, S. (2012). Mechanical work and physiological responses to simulated cross country mountain bike racing. *J Sports Sci, 30*(14), 1491-1501. doi:10.1080/02640414.2012.711487

Martin, L., Lambeth-Mansell, A., Beretta-Azevedo, L., Holmes, L. A., Wright, R., & St Clair Gibson, A. (2012). Even between-lap pacing despite high within-lap variation during mountain biking. *Int J Sports Physiol Perform, 7*(3), 261-270. doi:10.1123/ijspp.7.3.261

Miller, M. C., Fink, P. W., Macdermid, P. W., Allen, D., & Stannard, S. R. (2018). Braking and performance characteristics of experienced and inexperienced mountain bikers navigating an isolated off-road turn using a brake power meter. *International Journal of Performance Analysis in Sport, 18*(4), 495-506. doi:10.1080/24748668.2018.1496383

Miller, M. C., Fink, P. W., Macdermid, P. W., & Stannard, S. R. (2019). Quantification of brake data acquired with a brake power meter during simulated cross-country mountain bike racing. *Sports Biomech, 18*(4), 343-353. doi:10.1080/14763141.2017.1409257

Miller, M. C., & Macdermid, P. W. (2015). Predictive Validity of Critical Power, The Onset of Blood Lactate and Anaerobic Capacity for Cross-Country Mountain Bike Race Performance. *Sports and Exercise Medicine Open Journal, 1*(4), 105-110. doi:10.17140/semoj-1-118

Miller, M. C., Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2016). Agreement between Powertap, Quarq and Stages power meters for cross-country mountain biking. *Sports Technology, 8*(1-2), 44-50. doi:10.1080/19346182.2015.1108979

Miller, M. C., Macdermid, P. W., Fink, P. W., & Stannard, S. R. (2017). Performance and physiological effects of different descending strategies for cross-country mountain biking. *Eur J Sport Sci, 17*(3), 279-285. doi:10.1080/17461391.2016.1237550

Miller, M. C., Moir, G. L., & Stannard, S. R. (2014). Validity of using functional threshold power and intermittent power to predict cross-country mountain bike race outcome. *Journal of Science and Cycling, 3*(1), 16-20.

Novak, A. R., Bennett, K. J. M., Fransen, J., & Dascombe, B. J. (2018). A multidimensional approach to performance prediction in Olympic distance cross-country mountain bikers. *J Sports Sci, 36*(1), 71-78. doi:10.1080/02640414.2017.1280611

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. doi:10.1080/00140138808966766

Skiba, P. F., Jackman, S., Clarke, D., Vanhatalo, A., & Jones, A. M. (2014). Effect of work and recovery durations on W' reconstitution during intermittent exercise. *Med Sci Sports Exerc, 46*(7), 1433-1440. doi:10.1249/MSS.0000000000000226

Swain, D. P. (1997). A model for optimizing cycling performance by varying power on hills and in wind. *Med Sci Sports Exerc, 29*(8), 1104-1108. doi:10.1097/00005768-199708000-00017

Triska, C., Karsten, B., Beedie, C., Koller-Zeisler, B., Nimmerichter, A., & Tschan, H. (2018). Different durations within the method of best practice affect the parameters of the speed-duration relationship. *Eur J Sport Sci, 18*(3), 332-340. doi:10.1080/17461391.2017.1418025

Triska, C., Karsten, B., Heidegger, B., Koller-Zeisler, B., Prinz, B., Nimmerichter, A., & Tschan, H. (2017). Reliability of the parameters of the power-duration relationship using maximal effort time-trials under laboratory conditions. *PLoS ONE, 12*(12), e0189776. doi:10.1371/journal.pone.0189776

Tucker, R., & Noakes, T. D. (2009). The physiological regulation of pacing strategy during exercise: a critical review. *Br J Sports Med, 43*(6), e1. doi:10.1136/bjsm.2009.057562

Viana, B. F., Pires, F. O., Inoue, A., & Santos, T. M. (2018). Pacing Strategy During Simulated Mountain Bike Racing. *Int J Sports Physiol Perform, 13*(2), 208-213. doi:10.1123/ijspp.2016-0692

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*Appendix 1*

**Reliability of WAHOO KICKR**

The development of portable power meters has allowed cyclists greater control over performance both in competition and training. These are applicable to both outdoor and indoor training coupled with stationary strainers such as Wahoo KICKR. To be able to use these tools effectively it is paramount that they can accurately determine workloads and monitor progress. Identifying discrepancies allow for the athlete to assess how to best incorporate the device in their training. Multiple studies have concluded that the WHAOO KICKR are reliable (Hoon, Michael, Chapman, & Areta, 2016; Michael, Hoon, Areta, Patton, & Chapman, 2017; Zadow, Kitic, Wu, & Fell, 2018; Zadow, Kitic, Wu, Smith, & Fell, 2016), but display some intra unit variability (Hoon et al., 2016). Consequently, the aim of this pilot study was to assess the reliability of WAHOO KICKR for use with participants cycle mounted power meter.

**Methods**

Four workloads with a cadence of 70 rpm and 100 rpm will be used to assess the reliability and validity of the Wahoo KICKR (Wahoo Fitness,  Atlanta, USA). Each workload was maintained for 30 seconds at either 70 or 100 rpm before termination of workload, data on each workload were averaged after an initial 5 sec ramp up to workload power (Figure 1).  The test encompass performance on each workload, 150W, 250W, 350W and 450W, in that order. Power-meters were calibrated as by manufacturer recommendations.

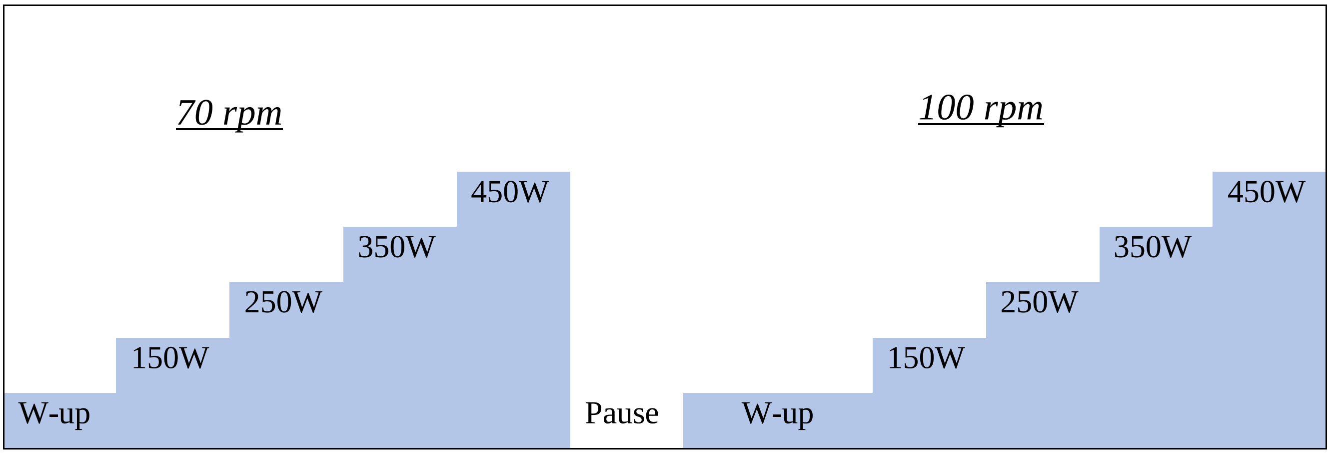



*Figure 1 Illustration of test protocol for assessing reliability of WAHOO KICKR.  Stepwise work rates for each cadence.*

The same participant completed all trials, on the same bicycle equipped with an SRM power meter (Schoberer Rad Meßtechnik, Jülich, Germany) and Vector 3 pedals (Garmin, Kansas USA). Though the SRM appears to underestimate peak power output, it is still thought to be one of the most useful tools for quantifying power output (Hoon et al., 2016; Zadow et al., 2018). Based on the recommendations of Atkinson and Nevill (1998), 95% limits of agreement were calculated based on the methods of Bland-Altman so that 95% of the differences between two power meters lie between the mean bias ± (standard deviation (SD) * 1.96).

**Results and conclusion**

The mean average difference between SRM and KICKR was 3.8 ± 1.8 % (Table 1), while the mean difference between Garmin and SRM was 1.8 ± 0.7 %.  Average Coefficient of variation for SRM was 1.2 ± 0.2 %. Bland-Altmann plots for Wahoo compared with SRM for all workloads can be seen in Figure 2A, and for Garmin compared with SRM in Figure 2B with.

Given the low difference between the portable power meters for all workloads, and the small variation seen in SRM. We conclude for the purposes of this study that the wahoo kickr is reliable, however, it systematically underestimates power output in relation to both power meters, questioning the validity of workload reported by the WAHOO KICKR.

***Table 1*** *Difference in mean between Wahoo KICKR and SRM power meter. There seem to be a progressive increase in difference between the two measurements, however, there is little variation in standard deviation and coefficient of variation in SRM. Suggesting that the measurement is reliable, though the validity should be questioned. Values are presented as mean ± standard deviation*

| | **Wahoo mean (W)** | **SRM mean (W)** | **Difference in mean (W)** | **Difference in mean (%)** | **SRM CV (%)** |
|---|---|---|---|---|---|
| Test 1 | 150.0 ± 0.1 | 151.5 ± 1.6 | 1.5 | 1.0 | 1.1 |
| Test 2 | 249.3 ± 2.6 | 258.8 ± 3.7 | 9.4 | 3.8 | 1.4 |
| Test 3 | 349.7 ± 2 | 367.7 ± 5 | 18.0 | 5.1 | 1.4 |
| Test 4 | 450.0 ± 0.9 | 474.2 ± 3.8 | 24.3 | 5.4 | 0.8 |

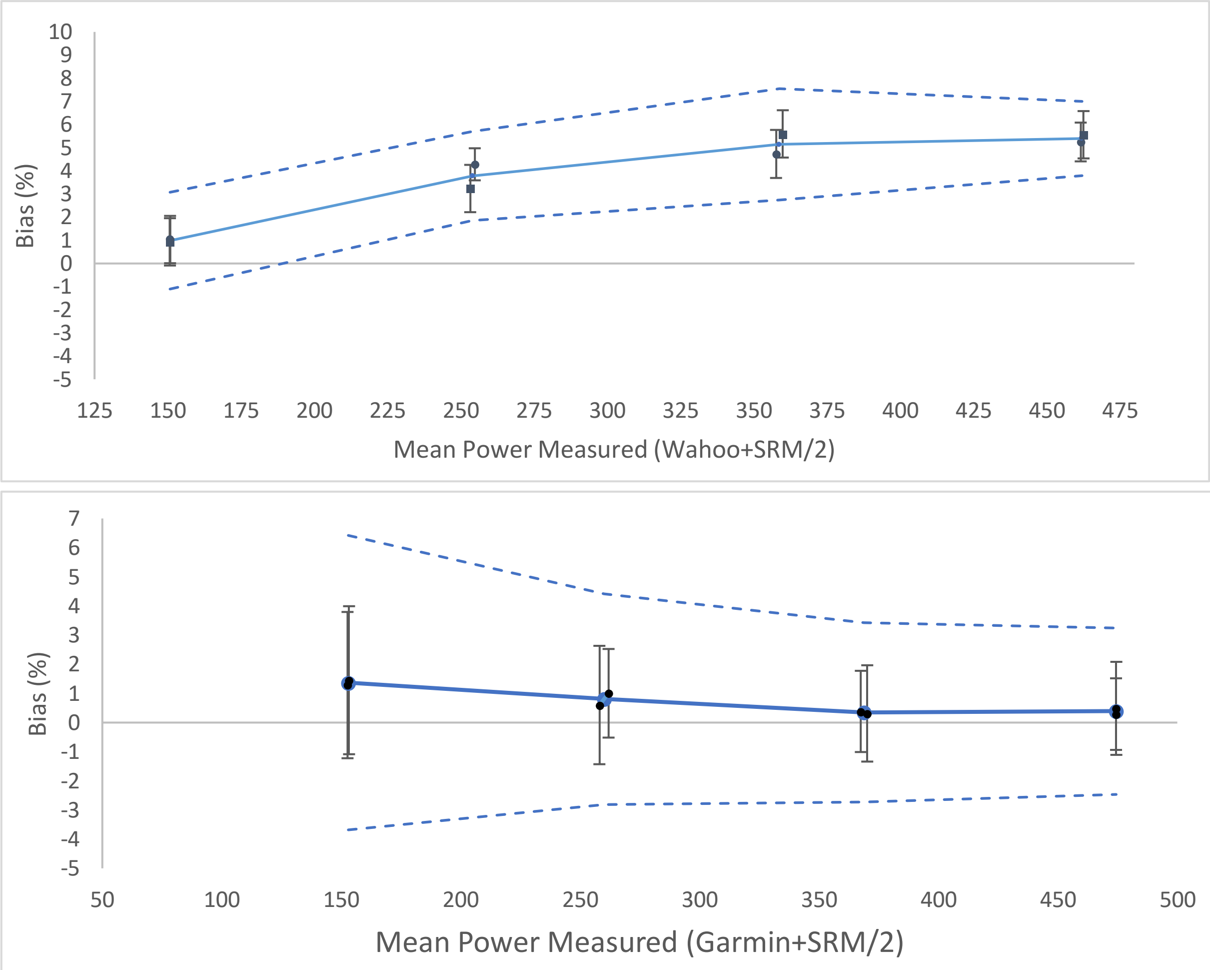



***Figure 2*** *Bland-Altmann plot for mean bias for (A) Wahoo compared to SRM, (B) SRM compared to Garmin. This displays a bias of underestimation for WAHOO, increasing at higher power output. The low difference between Garmin and SRM supports the reliability of the WAHOO KICKR, Cadence did not seem to significantly affect the power output readings for any of the three measurement devices tested.*

## Literature


Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Med, 26*(4), 217-238. doi:10.2165/00007256-199826040-00002

Hoon, M., Michael, S., Chapman, P., & 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. Retrieved from https://www.researchgate.net/publication/313881132

Zadow, E. K., Kitic, C. M., Wu, S. S., & Fell, J. W. (2018). Reliability of power settings of the Wahoo KICKR power trainer after 60 hours of use. *International Journal of Sports Physiology and Performance, 13*(1), 119-121.

Zadow, E. K., Kitic, C. M., Wu, S. S., Smith, S. T., & Fell, J. W. (2016). Validity of Power Settings of the Wahoo KICKR Power Trainer. *Int J Sports Physiol Perform, 11*(8), 1115-1117. doi:10.1123/ijspp.2015-0733

*Appendix 2*

## Estimation of critical power

As proposed by Triska et al. (2017), a test day for familiarisation can increase the precision of the CP estimate.

A significant difference was detected from familiarization day to test day one, with a mean increase of 9.4 ± 5.9W on TT12 ($t(5)=3.856$, $p = 0.012$) , a mean increase of 10.9 ± 4.9 W on TT7 ($t(5)=5{,}425$, $p = 0.003$) and an increase of 12.6 ± 5.4 W on TT3 ($t(5)=5.721$, $p = 0.002$). Significant difference in calculated CP was also found, with a mean increase of 8.8 ± 6.3 W increase from Familiarization to Test day 1 ($t(5)=3.372$, $p = 0.020$). No significant difference between test days were found for the W' parameter.

The CP parameter did indeed benefit from a day of familiarization. The W' parameter did not improve in precision by using one familiarization day and were still not viable. FP6 completed the familiarization, but not the test day, but CP estimate were inside the proposed 5% limit to error of estimate (4.7 %) and were included in further analysis.

***Table 1*** *Estimations of CP and the W' for familiarization and test day, reported as calculated CP and W' with standard error of estimate.*

| FP | Familiarization | | | | Test day | | | |
|---|---|---|---|---|---|---|---|---|
| | CP | SEE | W' | SEE | CP | SEE | W' | SEE |
| 2 | 375 | 15 | 23434 | 4046 | 389 | 8 | 24305 | 2315 |
| 3 | 349 | 14 | 12811 | 3852 | 358 | 8 | 12533 | 2219 |
| 4 | 446 | 6 | 17568 | 1532 | 456 | 11 | 16881 | 2961 |
| 5 | 274 | 2 | 6818 | 500 | 274 | 6 | 10303 | 1736 |
| 7 | 224 | 6 | 9247 | 1556 | 241 | 0.3 | 8787 | 75 |
| 8 | 243 | 0.1 | 6678 | 30 | 246 | 1.2 | 7997 | 336 |
| 6 | 338 | 16 | 15310 | 4406 | | | | |

Triska, C., Karsten, B., Heidegger, B., Koller-Zeisler, B., Prinz, B., Nimmerichter, A., & Tschan, H. (2017). Reliability of the parameters of the power-duration relationship using maximal effort time-trials under laboratory conditions. *PLoS ONE*, 12(12), e0189776. doi:10.1371/journal.pone.0189776

## List of Attachments

1. Letter from Local Ethics Committee at the Norwegian School of Sports Sciences
2. Forespørsel om å delta i prosjektet: Hva er de fysiologiske kravene under rundbane terrengsykkelritt
3. Spørreskjema dagsform og utmattelse

## Attachment 1: Letter from Local Ethics Committee at the Norwegian School of Sports Sciences

Thomas Losnegard
Seksjon for fysisk prestasjonsevne                                                    OSLO 05. september 2019

## Søknad 106-290819 – Hva er de fysiologiske kravene for rundbane terrengsykling

Vi viser til søknad, prosjektbeskrivelse, informasjonsskriv, innsendt melding til NSD og innhentet tilleggsinformasjon mottatt i mail datert 30.august 2019.

I henhold til retningslinjer for behandling av søknad til etisk komite for idrettsvitenskapelig forskning på mennesker, ble det i komiteens møte av 29. august 2019 konkludert med følgende:

**Vurdering**

I prosjektets utvalg er det kun menn som skal inkluderes. På bakgrunn av en noe mangelfull begrunnelse, ble det innhentet tilleggsinformasjon om dette. Komiteen vil bemerke at det er prosjektleders ansvar å tydelig begrunne sitt valg for utelukkelse av et kjønn i utvalget. Etter å ha mottatt ytterligere tilbakemelding for hvorfor bare menn vil bli inkludert, vurderer komiteen prosjektet som etisk forsvarlig. Det presiseres imidlertid at det for fremtidige prosjekter skal legges vekt på å inkludere begge kjønn, og at eventuell avvik fra hovedregelen må begrunnes tydelig og underbygges faglig.

**Vedtak**

*På bakgrunn av forelagte dokumentasjon finner komiteen at prosjektet er forsvarlig og at det kan gjennomføres innenfor rammene av anerkjente etiske forskningsetiske normer nedfelt i NIHs retningslinjer. Til vedtaket har komiteen lagt følgende forutsetning til grunn:*

- *Vilkår fra NSD følges*

Komiteen gjør oppmerksom på at vedtaket er avgrenset i tråd med fremlagte dokumentasjon. Dersom det gjøres vesentlige endringer i prosjektet som kan ha betydning for deltakernes helse og sikkerhet, skal dette legges fram for komiteen før eventuelle endringer kan iverksettes.

Med vennlig hilsen
Professor Sigmund Loland
Leder, Etisk komite, Norges idrettshøgskole

NORGES IDRETTSHØGSKOLE

## Attachement 2: Forespørsel om deltakelse i forskningsprosjektet

# *HVA ER DE FYSIOLOGISKE KRAVENE UNDER RUNDBANE TERRENGSYKKELRITT?*

Dette er et spørsmål til deg om deltakelse i et forskningsprosjekt for å undersøke fysiologiske arbeidskrav i terrengsykling. Siden terrengsykling innebærer varierende hastighet grunnet opp- og nedoverbakker er det trolig at intensitet vil variere betydelig under et ritt. Mer spesifikt ønsker vi å se på hva intensitet under et ritt med bruk av en metode som kalles "Critical power". "Critical power" er antatt å være den høyeste effekten du kan opprettholde under kontinuerlig langvarig arbeid. Vi vil teste din «Critical Power» i laboratorium og studere hvordan watt under rittet varierer i forhold til din «Critical power».

### Hva innebærer prosjektet?

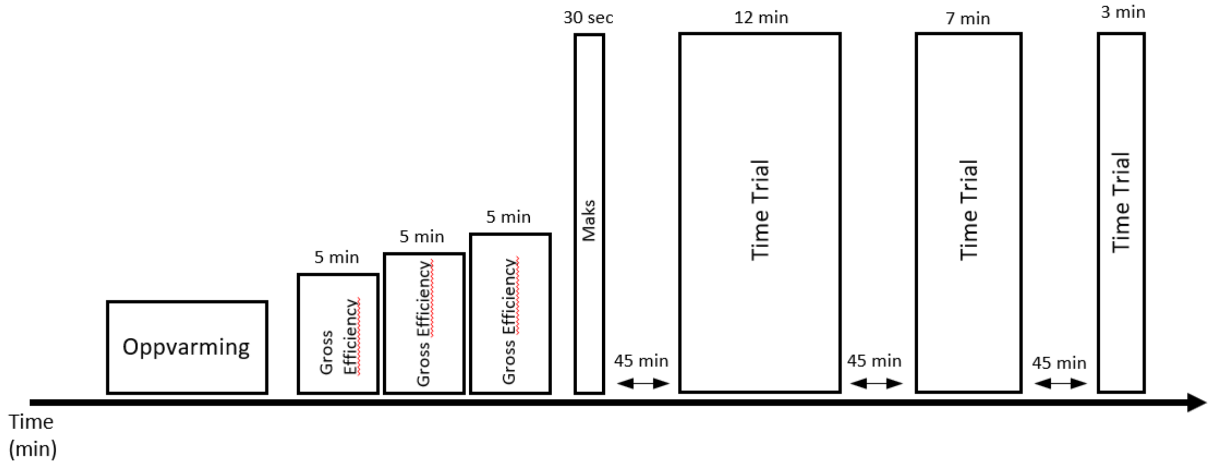
Studien innebærer at du må være tilgjengelig totalt 3 dager. Første testdag innebærer deltagelse i et terrengsykkelritt og testdag **2** og **3** innebærer gjennomføring av tester ved Norges Idrettshøgskole.

Første testtestdag vil være Norgescuprunden 14. september i Halden, og innebærer normal deltagelse i eliteklassen. Her gjennomføres rittet etter beste evne med kraftmåler allerede i bruk på egen sykkel, kontinuerlig pulsmåling samt en bærbar GPS festet med en vest mellom skulderbladene under uniformen.

Ved testdag **2** og **3** må du være tilgjengelig 4 timer per testdag. Under disse to testdagene skal du gjennomføre en effektivitets test, en maks 30 sekunders test og tre tidsbestemte maksimale tester for kalkulering av «Critical Power». Testene gjøres på egen sykkel på fastmontert rulle.

På testtestdag 2 og 3 vil du gjennomføre protokollen som skissert under og illustreres i figur 1. Disse testtestdagene er like, men testdag 2 vil fungere som en tilvenning til testdag tre, hvor vi i tillegg måler oksygenopptak. Det vil være minst 48 timer mellom testtestdagene. Testene gjøres på egen sykkel fastmontert på rulle, og med kontinuerlig oksygenopptaksmåling via munnstykke med klype over nesen. Du vil bli informert om tid gjennom testene. På testdag 2 og 3 gjennomfører du følgene:

1) Fem minutter rolig oppvarming etterfulgt av tre 5 minutters drag på lav til moderat intensitet med økende grad. På disse testene undersøker vi energiforbruket ditt relativt til ytre belastning (effektivitet, «Gross Efficiency»).
2) 30 sekunders test, med måling av maks og gjennomsnitts kraft. Testen gjennomføres med maksimal innsats.
3) Etter 45 minutters pause, følger en av tre makstester på henholdsvis 12, 7 eller 3 minutter i tilfeldig rekkefølge.
    a. Etter en ny 45 minutter pause gjennomføres neste tilfeldig maksimal test.
    b. En siste 45 minutter pause før gjenstående maksimal test.




*Figur 1: Skjematisk oversikt over testene for testdag 2-3.*

**Mulige fordeler og ulemper**

Du får et verdifullt innblikk i fysiologiske faktorer som kan hjelpe deg i treningen din. Du får vite din $VO_2$maks og hvor effektivt du sykler (Gross Efficiency). I tillegg får du kunnskap om hvilke fysiologiske krav terrengsykkel rundbane krever og innsikt i hvordan forskning gjennomføres. Videre kan resultatene fra studien gi deg informasjon om hvordan du kan bruke «Critical power» for din trening.

Deltakelse i studien vil kreve oppmøte på 4 timer over 2 dager (i tillegg til rittet) med minst 72 timer mellom hver testtestdag. Ved oksygenopptaksmålinger benyttes det et munnstykke som kan oppleves noe ubehagelig, samt at du kan oppleve å bli tørr i halsen. Munnstykket er desinfisert før bruk. Testene kan oppleves som meget anstrengende.

**Frivillig deltakelse og mulighet for å trekke sitt samtykke**

Det er frivillig å delta i prosjektet. Dersom du ønsker å delta, undertegner du samtykkeerklæringen på siste side. Samtykke er det lovlige behandlingsgrunnlaget for behandling av personopplysninger. Du kan når som helst og uten å oppgi noen grunn trekke ditt samtykke. Dette vil ikke få konsekvenser for deg. Dersom du trekker deg fra prosjektet, kan du kreve å få slettet innsamlede prøver og opplysninger, med mindre opplysningene allerede er inngått i analyser eller brukt i vitenskapelige publikasjoner. Dersom du senere ønsker å trekke deg eller har spørsmål til prosjektet, kan du kontakte Steffan Næss på telefon 418 45 048 eller e-post: steffan@impression.no, eller Prosjektleder: Thomas Losnegard på telefon 997 34 184 eller e-post: thomas.losnegard@nih.no

**Hva skjer med informasjonen om deg?**

Informasjonen som registreres om deg skal kun brukes slik som beskrevet i hensikten med studien. Du har rett til innsyn i hvilke opplysninger som er registrert om deg og rett til å få korrigert eventuelle feil i de opplysningene som er registrert.

Informasjonen som blir samlet vil være tilgjengelig for prosjektmedarbeider, og vil inkludere: navn, fødselsdato, telefonnummer, e-post, høyde, vekt, samt helseforholdene maksimalt oksygenopptak, Gross efficiency og Critical Power.

Alle opplysningene vil bli behandlet uten navn og fødselsnummer eller andre direkte gjenkjennende opplysninger. En kode knytter deg til dine opplysninger gjennom en navneliste, og koblingsnøkkelen mellom navn og kode oppbevares i en låst safe.

Prosjektleder har ansvar for den testdaglige driften av forskningsprosjektet og at opplysninger om deg blir behandlet på en sikker måte. Prosjektslutt er 01.09.2024, og alt datamateriale anonymiseres innen denne datoen.

Deltakerne har rett til å få utlevert en kopi av opplysningene som er registrert (dataportabilitet), samt rett til å sende klage til personvernombudet (personvernombudet@nsd.no, +47 55 58 21 17) eller Datatilsynet angående behandlingen av personopplysninger

## Forsikring

NIH er en statlig institusjon og er dermed selvassurandør. Eventuelle skader på deltakere i forbindelse med prosjektet vil bli dekket av NIH.

## *Økonomi*

Reisekostnader knyttet til prosjektet vil støttes gjennom forskningsmidler fra Seksjonen for fysisk prestasjonsevne ved Norges idrettshøgskole.

### *Godkjenning*

Prosjektet er godkjent av Lokal etisk komite ved Norges idrettshøgskole, [106-290819). Prosjektet er meldt til Personvernombudet for forskning, NSD - Norsk senter for forskningsdata AS

*Samtykke til deltakelse i PROSJEKTET*

Jeg er villig til å delta i prosjektet

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Sted og dato Deltakers signatur

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Deltakers navn med trykte bokstaver

Jeg bekrefter å ha gitt informasjon om prosjektet

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Sted og dato Signatur

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Rolle i prosjektet

## Attachement 3: Spørreskjema om søvn, dagsform og utmattelse

### ***Rittdag***

***Før ritt***

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. Hvor mange timer sov du i natt? | **Timer:** | | | | | **Minutter** | | | | | |
| 2. Hvor godt sov du i natt på en skala fra 1-10 hvor 1 er dårligst og 10 er best - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |
| 3. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | |

***Etter ritt***

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4. Hvor hardt var rittet på en skala fra 1-10 hvor 1 er lett og 10 er veldig tungt - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 5. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 6. Hadde du noen problemer med utstyr eller annet på ritt dag? | **Ja** | | | | | **Nei** | | | | |

### ***Laboratorium dag 1***

***Før prestasjonstester***

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Hvor mange timer sov du i natt? | **Timer:** | | | | | **Minutter** | | | | |
| 2. Hvor godt sov du i natt på en skala fra 1-10 hvor 1 er dårligst og 10 er best - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 3. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

***Etter prestasjonstester***

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4. Hvor hard var testene på en skala fra 1-10 hvor 1 er lett og 10 er veldig tungt - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 5. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

### ***Laboratorium dag 2***

***Før prestasjonstester***

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 1. Hvor mange timer sov du i natt? | **Timer:** | | | | | **Minutter** | | | | |
| 2. Hvor godt sov du i natt på en skala fra 1-10 hvor 1 er dårligst og 10 er best - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 3. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |

***Etter prestasjonstester***

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 4. Hvor hard var testene på en skala fra 1-10 hvor 1 er lett og 10 er veldig tungt - ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 5. Hvordan føler du din dagsform har vært på en skala fra 1-10 hvor 1 er dårligst og 10 er best – ring rundt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |