# Functional Thresholds and its Association with 20- and 40km Cycling Performance

by

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*Thesis presented in fulfilment of the requirements for the degree of Master in Science in Sport Science in the Department of Exercise, Sport and Lifestyle Medicine, Sports Science, Faculty of Medicine and Health Sciences at Stellenbosch University.*

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December 2022

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# ACKNOWLEDGEMENTS

*It is with great gratitude and thankfulness that I write these acknowledgements.*

**Prof Elmarie Terblanche**: thank you for your firm, yet patient guidance over these past two years. I have learned and grown so much under your supervision. Your expertise in the field is truly admirable. Thank you for your excellent mentorship and effort to make the completion of my MSc thesis a reality.

**Ms Louise Engelbrecht:** thank you Louise for mentoring and guiding me in the laboratory with the new and daunting equipment. Thank you that you were always willing to give insights and ideas!

**My parents:** Thank you for allowing me this opportunity to complete my MSc thesis. Without your continuous support, care and love throughout this process - through the ups and downs - I definitely would have given up. I am truly, forever grateful. Thank you.

**My God:** Thank you Father God for these past two years. You used my MSc journey to shape me - teaching me patience and persistence. You also taught me to not let anxiety get a hold on me, and to keep my eyes fixed on You in both the good and challenging times. I am forever grateful.

# SUMMARY

Functional Threshold Power (FTP) and Critical Power (CP) are both functional thresholds that potentially are more comprehensive measures of an athlete's cycling endurance performance capabilities compared with metabolic (lactate) thresholds, which are limited to the functioning of a single metabolic parameter. The functional thresholds are based on the measurement of mechanical work (i.e., power output) and exercise tolerance and are also readily accessible to coaches and athletes of all levels.

The purpose of this study was to examine the association of CP and FTP with cycling time trial performance in a laboratory setting. §Thirteen trained to well-trained MTB riders, including men (n = 8) and women (n = 5), aged between 19 and 51 years, participated in this study. The cycling tests included a ramp incremental test to exhaustion, a 3-min all-out test, a 20-min FTP test, a 20 km (TT2) and 40 km (TT40) time trial. Inferential statistical analysis was done to examine the relationships between CP, FTP, peak power output (PPO), $VO_{2max}$, TT20 and TT40. Significant correlations were observed between CP, FTP, PPO and $VO_{2max}$ ($r = 0.58$ to $0.97$, $p < 0.05$), but not between *absolute* CP and $VO_{2max}$ ($r = 0.40$, $p > 0.05$). PPO (338 ± 74 W, 4.7 ± 0.6 W·kg$^{-1}$), CP (291 ± 78 W, 4.0 ± 0.7 W·kg$^{-1}$) and FTP (230 ± 63 W, 3.2 ± 0.6 W·kg$^{-1}$) were significantly correlated to TT20 and TT40 performance times ($r = 0.75$ to $0.97$, $p < 0.001$). *Absolute* FTP was more strongly correlated to TT20 and TT40 than CP ($r = 0.97$ and $0.89$ *vs.* $r = 0.75$ and $0.78$, $p < 0.001$). Even though the power outputs at FTP and CP were significantly correlated ($r = 0.90$ to $0.96$, $p < 0.001$), the moderate to low ICC scores (*relative*: 0.21 and *absolute*: 0.68), suggests that these two thresholds should not be used interchangeably. The *absolute* PPO was significantly higher than the power outputs at CP and FTP, while no significant difference was observed between the power outputs at CP and FTP. The *relative* power outputs were significant different between the power outputs at CP and FTP, but not between PPO and CP. The calculated effect sizes between both *relative* and *absolute* measures (ES = 0.61 and 0.38, respectively) suggest that the differences between the power outputs are practically meaningful, even though they were not statistically significantly different. It was concluded that both functional thresholds, CP and FTP (*absolute* and *relative* measures), are valid and valuable measures of cycling endurance performance for 20 km and 40 km distances. Of the two thresholds, *absolute* FTP had the strongest association with cycling time trial performance in a laboratory setting.

# OPSOMMING

Funksionele Draaipunt Krag (FTP) en Kritieke Krag (CP) is beide funksionele draaipunte wat potensieel meer omvattende bepalers is van ‘n atleet se fietsry uithouvermoë-prestasie as metaboliese (laktaat) draaipunte, wat beperk is tot die funksionering van ‘n enkele metaboliese parameter. Die funksionele draaipunte is gebaseer op die meting van meganiese werk (bv. kraguitset) en oefening toleransie en is ook geredelik toeganklik vir afrigters en atlete van alle vlakke.

Die doel van hierdie studie was om die voorspellende waarde van FTP en CP op ‘n fietsry tydtoets-prestasie te bepaal binne ‘n laboratorium situasie. Dertien geoefende tot goed-geoefende berg-fietryers, insluitende mans (n=8) en vroue (n=5), tussen die ouderdom van 19 en 51 jaar, het aan hierdie studie deelgeneem. Die fietsry toetse het ‘n inkrementele stap-toets tot vermoeienes, ‘n 3-min maksimale toets, ‘n 20-min FTP toets, ‘n 20 km (TT20) -en 40 km (TT40) tydtoets ingesluit. Betekenisvolle verwantskappe is opgemerk tussen CP, FTP, PPO en $VO_{2max}$ ($r = 0.58$ tot 0.97, $p < 0.05$), maar nie tussen *absolute* CP en $VO_{2max}$ ($r = 0.40$, $p > 0.05$) nie. PPO (338 ± 74 W, 4.7 ± 0.6 $W \cdot kg^{-1}$), CP (291 ± 78 W, 4.0 ± 0.7 $W \cdot kg^{-1}$) en FTP (230 ± 63 W, 3.2 ± 0.6 $W \cdot kg^{-1}$) was betekenisvol geassosieer met TT20 and TT40 prestasietye ($r = 0.75$ tot 0.97, $p < 0.001$). *Absolute* FTP het beter gekorreleer met TT20 en TT40 as CP ($r = 0.97$ en 0.89 *vs.* $r = 0.75$ en 0.78, $p < 0.001$). Al het die kraguitsetwaardes van FTP en CP sterk gekorreleer ($r = 0.90$ to 0.96, $p < 0.001$), stel die matig tot lae ICC tellings (relatief: 0.21 en absoluut: 0.68) voor dat hierdie twee draaipunte nie gelykwaardig is nie. Die *absolute* PPO was betekenisvol hoër as die kraguitset by CP en FTP, terwyl geen betekenisvolle verskil opgemerk is tussen die kraguitsetwaarde by CP en FTP nie. Die relatiewe kraguitsetwaardes was betekenisvol verskillend van die kraguitsetwaardes by CP en FTP, maar nie tussen PPO en CP nie. Die effekgrootte tussen beide *relatiewe* en *absolute* metings (ES = 0.61 en 0.38, onderskeidelik) stel voor dat die verskille tussen kraguitsetwaardes prakties betekenisvol is, selfs al was dit nie statisties betekenisvol verskillend nie. Daar is tot die gevolgtrekking gekom dat beide funksionele draaipunte, CP en FTP (*absolute* en *relatiewe* afmetings), geldige en betekenisvolle voorspellers is van fietsry uithouvermoë-prestasie oor 20 km en 40 km. Van die twee draaipunte, was *absolute* FTP die beste voorspeller van ‘n laboratorium-gebaseerde fietsry tydtoets prestasie.

# GLOSSARY

## LIST OF ABBREVIATIONS

| | |
|---|---|
| ATP: | adenosine triphosphate |
| CP: | critical power |
| ES: | effect size |
| F: | female |
| FTP: | functional threshold power |
| GET: | gaseous exchange threshold |
| $H^+$: | hydrogen ions |
| IAT: | individual anaerobic threshold |
| ICC: | intraclass correlation coefficient |
| kJ: | kilojoules |
| LoA: | limits of agreement |
| LT: | lactate threshold |
| M: | male |
| min: | minutes |
| MLSS: | maximal lactate steady state |
| MTB: | mountain bike |
| OBLA: | onset of blood lactate accumulation |
| p: | p-value |
| PCr: | phosphocreatine |
| pH: | potential of hydrogen |
| $P_i$: | inorganic phosphate |
| PPO: | peak power output |
| r: | Pearson correlation coefficient |
| RCP: | respiratory compensation point |
| TT: | time trial |
| TTE: | time to exhaustion |
| $VO_{2max}$: | maximal oxygen uptake |
| VT: | ventilatory threshold |
| $W'$: | W-prime |
| XCO-MTB: | cross-country Olympic mountain bike |
| Yr: | years |

# DEFINITIONS

**CP:** critical power is the threshold demarcating the heavy- to severe-intensity domains on the exercise intensity continuum (Jones *et al.*, 2019).

**Cycling Performance:** the time (min / sec), distance (km / m), or average power output (Watts) a cyclist achieves during a performance test / time trial.

**FTP**: functional threshold power is the highest power output that a cyclist can sustain for approximately 60-min without the onset of fatigue (Allen *et al.*, 2019).

**Functional Threshold:** a threshold determined through performance-based tests as a function of work done (e.g., power output) and the duration or distance of exercise (Allan & Coggan, 2006; Jones & Vanhatalo, 2017; Jones *et al.*, 2010a).

**GET**: the gaseous exchange threshold represent the exercise intensity where an increase in the $VCO_2$ / $VO_2$ relationship occurs, identified by the V-slope plot (Peinado, *et al.*, 2016; Poole, *et al.*, 2021).

**LT**: thresholds associated with lactate measurements.

**$LT_{Dmax}$** and **$LT_{mDmax}$**: the use of curve-fitting procedures to identify the lactate threshold (Bishop, *et al.*, 2000; Cheng, *et al.*, 1992).

**$LT_{1.0}$**: the exercise intensity where blood lactate levels rise with 1 $mmol.L^{-1}$ above baseline (Pfitzinger & Freedson, 1998).

**$LT_{2.0}$:** the exercise intensity eliciting fixed blood lactate concentrations of 2 $mmol.L^{-1}$ (Faude, Kindermann & Meyer, 2009).

**Metabolic Threshold:** a threshold determined by specific cardio-metabolic or gas exchange - and blood lactate parameters (Faude *et al.*, 2009; Jones & Carter, 2000) measured during an incremental aerobic capacity test to exhaustion.

**MLSS**: maximal lactate steady state represents the highest exercise intensity at which a lactate steady-state can be maintained (Faude *et al.*, 2009; Hall *et al.*, 2016; Jones *et al.*, 2019; Pringle & Jones, 2002).

**OBLA**: the onset of blood lactate accumulation at 4 $mmol.L^{-1}$ (Faude *et al.*, 2009).

**Power output:** cycling workload measured in Watts (W).

**PPO:** peak power output is the highest workload achieved during the ramp incremental cycling test.

**RCP:** respiratory compensation point refers to the $VO_2$ value corresponding to the point of departure from linearity of the $V_E$-versus-$VCO_2$ relationship (Bergstrom *et al.*, 2013).

**TT:** a time trial is a fixed distance / time interval that a cyclist needs to complete with a maximal effort.

**$VO_{2max}$**: maximal oxygen uptake ($ml.kg^{-}1.min^{-1}$) at or near the end of an incremental exhaustive aerobic capacity test.

**$VT_1$:** first ventilatory threshold represent the exercise intensity where an increase in the $VCO_2$ / $VO_2$ relationship occurs, identified by the V-slope plot (Peinado, *et al.*, 2016; Poole, *et al.*, 2021).

**$W'$:** W-prime is the curvature constant of the hyperbolic power-time curve (Poole, et al., 2016; Skiba, et al., 2015; Vanhatalo, et al., 2011).

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# Chapter 1 LITERATURE REVIEW

## 1.1 INTRODUCTION

What we know today about the factors associated with endurance performance have been built on the views and frameworks established by A.V. Hill and colleagues around 1923 (Bassett, 2002). Since then, as technology developed and research findings became universally accepted, factors associated with cycling endurance performance have been vastly explored and described. Controversies and disagreements arose, however, due to inconsistencies and variances in the methodology used to determine cycling endurance performance capacities. Faria *et al. (*2005) asserted that there is a great need for methodology standardization for findings to be useful at the operational level. To date, the existence of the vast majority of different exercise testing protocols and consequent complications have been highlighted by several authors (Capostagno *et al.*, 2016; Jones *et al.*, 2019; Poole *et al.*, 2021).

Due to the varying nature of cycling events (e.g., cross-country, road cycling, mountain biking) and different performance goals (e.g., sprint, endurance, ultra-endurance), different types of cycling performance tests are described in the literature. Laboratory exercise tests are often used to determine an athlete's limit of exercise tolerance in an effort to predict cycling performance in the field. These tests include incremental tests-to-exhaustion (Amann *et al.*, 2006; Heuberger *et al.*, 2018; McNaughton *et al.*, 2006), time-to-exhaustion trials (Burnley *et al.*, 2006; Mattioni *et al.*, 2016; McClave *et al.*, 2011), maximal all-out efforts (Bergstrom *et al.*, 2013; Denham *et al.*, 2020; Francis *et al.*, 2010), sub-maximal tests (Capostagno *et al.*, 2016; Lamberts & Davidowitz, 2014) and time trials (MacInnis *et al.*, 2019; Maturana *et al.*, 2017; Peveler *et al.*, 2017). The metabolic and/or functional data collected during these tests are used to describe or evaluate a cyclist's performance capabilities, or to predict real-world performance. A problem that currently exists, is that a great variety of parameters, or thresholds, have been proposed as endurance performance indicators (Amann *et al.*, 2006; Bentley *et al.*, 2001; Burnley & Jones, 2007; García-García *et al.*, 2018; Jones *et al.*, 2019; Lamberts, 2014; Sanders *et al.*, 2017). Additionally, the methodology researchers use to determine these parameters or thresholds differs vastly and has led to much debate and confusion as to which threshold(s) are the best measures of endurance performance (Poole *et al.*, 2021).

Thresholds are depicted by specific changes in certain physiological parameters, and represent a 'tipping point' above and below which unique mechanisms of physiological control exist (Poole *et al.*, 2021). Changes in oxygen kinetics (Poole & Jones, 2012), ventilatory responses (Amann *et al.*, 2006; Keir *et al.*, 2018), blood lactate concentrations (Heuberger *et al.*, 2018), or power output (Bentley *et al.*, 2001; Vanhatalo *et al.*, 2008) give insight to specific metabolic events, e.g., the dominant energy pathway being utilized for ATP production (Baker *et al.*, 2010). The exercise intensity continuum can be divided into three domains, i.e., the moderate -, heavy -and severe exercise intensity domains, each with unique physiological underpinnings and demarcated by specific threshold(s) (Black *et al.*, 2017; Jones *et al.*, 2019) (Fig 1-1 below). A continuing topic of debate amongst researchers in the field entails which of the existing metabolic / functional thresholds should be used to depict the boundaries of the three exercise intensity domains (Poole *et al.*, 2021).

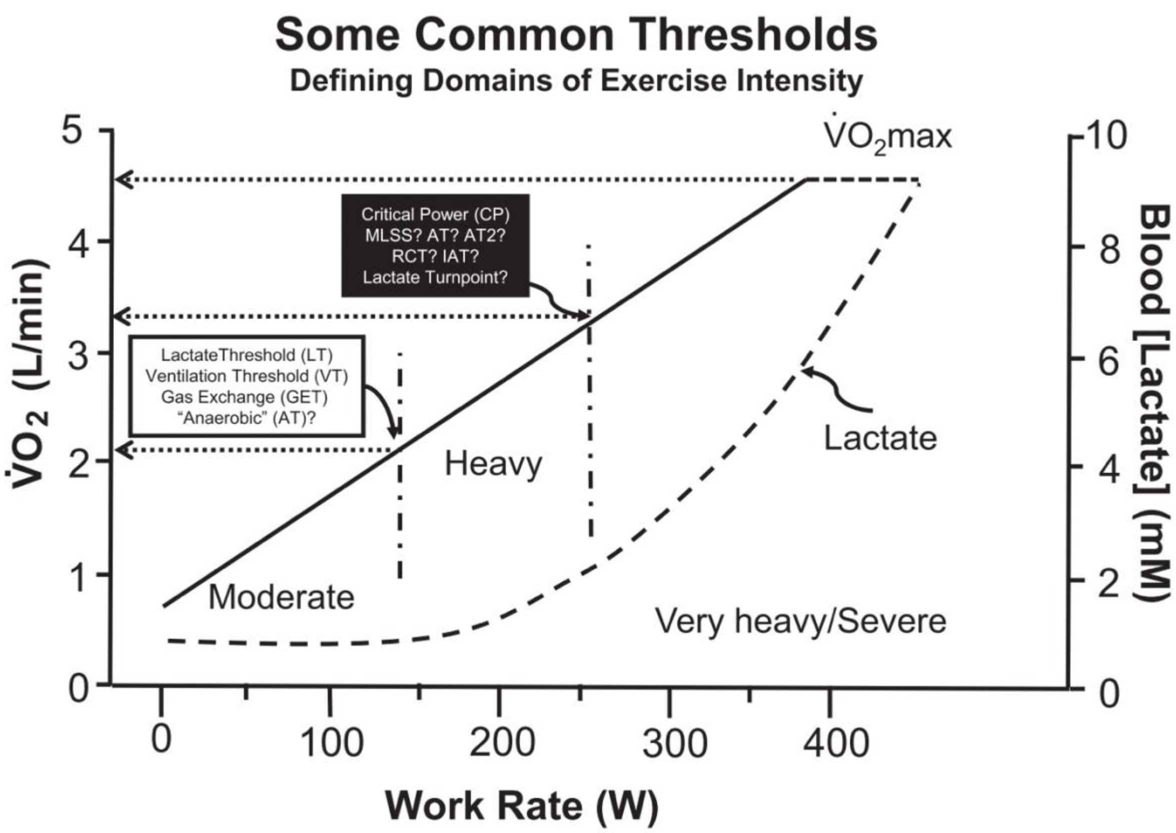



**Figure 1-1: Common thresholds defining the exercise intensity domains (Poole *et al.*, 2021)**

In the literature, two categories of thresholds are described. Firstly, the conventional metabolic thresholds, which are determined by specific cardio-metabolic or gas exchange -and blood lactate parameters (Faude *et al.*, 2009; Jones & Carter, 2000) measured during an incremental capacity test to exhaustion. Secondly, functional thresholds, which are determined through performance-based tests as a function of work done (e.g., power output) and the duration or distance of exercise (Allan & Coggan, 2006; Jones & Vanhatalo, 2017; Jones *et al.*, 2010).

It is well known that endurance performance is a complex and integrated system of cardio-respiratory and metabolic control (Ferretti, 2015). On top of that, an athlete's pacing strategy, mental fatigue and lactate tolerance also contribute to endurance exercise performance (Marcora & Staiano, 2010; Skorski & Abbiss, 2017). Therefore, functional thresholds are regarded objective measures of work done against time, a true representation of actual performances (e.g., races; events; time trials) and not limited to singular metabolic parameters. Subsequently, functional thresholds have been promoted as more comprehensive in nature compared to the more traditional metabolic thresholds (Allen *et al.*, 2019; Jones *et al.*, 2019). Today, the use of mobile power meters and cycle ergometers as a training tool have become widespread and allows for a direct, objective assessment of cycling performance (Allan & Coggan, 2006; Sitko *et al.*, 2020), as well as functional thresholds. Therefore, an advantage of functional thresholds is that they do not require expensive laboratory equipment and expertise on the interpretation of the metabolic measurements; thus, they are more accessible to coaches and athletes.

Time trials are popular exercise tests and have been shown to be valid performance tests as they closely represent actual performance in the field (Currell & Jeukendrup, 2008; Rosenblat, Lin, da Costa, *et al.*, 2021; Stevens & Dascombe, 2015). Time trials vary in nature, most commonly requiring cyclists to either complete a specific distance (e.g., 10 km or 40 km) in the shortest possible time, or to cover the greatest possible distance in a set time limit (e.g., 20 min or 60 min), or maintain the highest mean power output / velocity within the set time (Rosenblat *et al.*, 2021). Both 20 km and 40 km time trials have been shown to be reliable laboratory cycling performance tests (Palmer et al., 1996; Sporer et al., 2007). The latter is most commonly used to predict performance in the field and to assess physiological mechanisms underlying cycling endurance performance (Paton et al., 2001; Stevens et al., 2015).

## 1.2 FUNCTIONAL THRESHOLD POWER

### 1.2.1 What is FTP and where does it come from?

The functional threshold power (FTP) concept was introduced by Hunter Allen and Andrew Coggan in their book "Training and Racing with a Power meter - edition one" in 2006. FTP is an *estimate* of the highest power output that a cyclist can maintain in a quasi-steady state for about 60 minutes without the onset of fatigue (Allen, *et al*., 2019). The rationale behind this concept, relates to the exercise intensity that associates with the lactate threshold where lactate production and removal achieve equilibrium, which is known to be a key physiological determinant of endurance performance across a range of different durations (Coyle *et al.*, 1988; Craig *et al.*, 1993; Faude *et al.*, 2009; Jones & Carter, 2000; Poole *et al.*, 2021). This lactate threshold is known as OBLA (onset of blood lactate accumulation, defined at a blood lactate concentration of 4 $mmol.L^{-1}$), MLSS (maximal lactate steady state), IAT (individual anaerobic threshold), and $LT_2$ (the second lactate threshold), which all conceptually signify the same physiological intensity (Poole et al., 2021). In other words, the underlying physiological notion of all the mentioned thresholds, including FTP, is that it represents the critical exercise intensity below which blood lactate accumulation and -removal achieve a steady state (Allen *et al.*, 2019; Borszcz *et al.*, 2019). In the light of several limitations identified in using laboratory-based exercise testing for training prescription and measuring cycling performance, the founders developed a more functional way of determining the exercise intensity which relates to this lactate threshold. These limitations included the unpracticality and high costs involved with laboratory metabolic data collection, making lactate testing inaccessible to many athletes; the unreliability of using heart rate as a measure of performance and exercise prescription; and the plethora of lactate threshold definitions that existed at that time, leading to a confusing and complicated process of measuring and monitoring cycling performance and training (Allen *et al.*, 2019). A recent publication elicits the challenges surrounding the lactate threshold (Poole *et al.*, 2021), which makes a more functional method of assessing, monitoring and predicting cycling performance appealing.

Contrary to traditional metabolic exercise testing, the founders suggested that a more direct and accessible means to estimate a cyclist's *functional* threshold power, is by measuring their average power output during a 60 minute time trial (Allen *et al.*, 2019). The term *functional* suggests that this threshold is a more practical or useful means of determining this threshold, as it is purely based on the measurement of power output and time. Thus, Allen and Coggan pioneered the use of mobile power meters as a training tool by arguing that power output is a much more direct, precise, and accurate measure of training intensity and cycling performance.

### 1.2.2 Methods to determine FTP

Allen and Coggan (2019) suggested several methods for estimating FTP, of which the most popular protocol being a 20 min time trial (TT) (Sitko *et al.*, 2020). A key component to this protocol was the very specific 45 min warm-up preceding the 20 min TT, which consists of: a) cycling for 20 min at low intensity, b) 3 x 1 min fast accelerations (>100 rpm) with 1 min recovery intervals of low intensity, c) 5 min at low intensity, d) a 5 min TT, and e) 10 min at low intensity. A 95% correction factor is then applied to the mean power output of the 20 min TT to give an FTP estimate (Allen *et al.*, 2019).

The validity of this protocol has been investigated and confirmed by Borszcz *et al.*, (2018). These authors reported that a strong relationship (r = 0.88), low bias (-4.4 W) and moderate LoA (-40 to 32 W) existed between the 60 min and 20 min FTP in a group of trained cyclists. Additionally, the mean time-to-exhaustion of the 20 min estimated FTP was 50.9 ± 15.7 min, which falls within the 45 - 60 min sustained exercise intensity associated with MLSS (Faude *et al.*, 2009).

Several authors questioned the correction factor of 95% (Inglis *et al.*, 2020; Lillo-Beviá *et al.*, 2019; MacInnis *et al.*, 2019), suggesting that a stronger correction factor of 90 % (MacInnis *et al.*, 2019) and 91% (Lillo-Beviá *et al.*, 2019) should rather be used to avoid an overestimation of FTP, especially when using a less intense warm-up than the original warm-up protocol. Others concurred with these authors (Borszcz *et al.*, 2019; Mackey & Horner, 2021; Tramontin, Borszcz & Costa, 2022), stating that the warm-up protocol influences the 20 min TT performance, and consequently, FTP . The inclusion of a 5 min TT as part of the warm-up (as originally proposed) leads to a more conservative pacing at the onset of the 20 min TT, and a reduced mean power output during the 20 min TT than when a 5 min TT is not included (Borszcz *et al.*, 2020; Tramontin *et al.*, 2022). Nevertheless, the 20 min TT is the most popular protocol in the literature to estimate FTP (Sitko *et al.*, 2020), although different warm-up protocols are performed prior to the test (Denham *et al.*, 2020; Inglis *et al.*, 2020; Jeffries *et al.*, 2019; Karsten *et al.*, 2015; Lillo-Beviá *et al.*, 2019; McGrath *et al.*, 2021; Valenzuela *et al.*, 2018).

It is recognised in the literature that a limitation of a time trial protocol, such as the 20 min FTP test, is that cyclists' experience and pacing comes into play, which greatly influence performance outcomes (Borszcz *et al.*, 2020; Hibbert *et al.*, 2017; Skorski & Abbiss, 2017). Hibbert *et al.*, (2017) examined the reproducibility of a 20 km TT in a group of recreationally active individuals (n = 30), with no prior time trial experience. These authors reported that the variability in mean power output across five 20 km time trials was reduced as more trials were performed, concluding that novice participants require three familiarization trials to establish reproducible outcomes. Others have shown that the performance of a 20 min TT in a group of highly trained cyclists and triathletes (n = 19) was repeatable with highly satisfactory limits of agreement (-17 W to +13), mean bias of (-2 W) (McGrath *et al.*, 2019). Collectively, these studies show that previous time trial experience has an affect on performance outcomes. Furthermore, it has been shown that pacing is influenced by several factors such as prior exercise, accumulated fatigue, mental fatigue and environmental conditions (Skorski & Abbiss, 2017). Additionally, as previously discussed, pacing is also affected by the warm-up prior to the time trial (Borszcz *et al.*, 2020; Tramontin *et al.*, 2022), which further highlights the limitations associated with time trial protocols to establish performance measures, such as FTP. These limitations lead to the exploration of using shorter time trial durations and alternative protocols to estimate FTP (Mackey & Horner, 2021; Sitko *et al.*, 2020), due to shorter tests eliciting less opportunity for pacing. An 8 min TT have been proposed by Carmichael & Rutberg, (2012), where FTP = mean power output of the 8 min TT x 0.90 (correction factor). This protocol, however, has not yet been compared to FTP from the 20 min TT. Denham *et al.*, (2020) explored the use of a traditional ramp incremental cycling test to estimate FTP, where FTP = PPO x 0.865 - 56.484. These authors found that FTP and peak power output (PPO) are significantly correlated ($r = 0.97$, $p < 0.001$), suggesting that the ramp incremental test offers an alternative test to estimate FTP. Some of the well-known virtual cycling platforms (e.g., Zwift and TrainerRoad) implemented a novel protocol to determine FTP. Here FTP is calculated as 75 % of the highest 1-min power output achieved during an incremental ramp test. The reasoning behind the latter approach is that it takes the problem of pacing out of the equation, thus, results are likely to be more reliable. However, it was concerning to note that no scientific publications could be found where this protocol, which is widely used by coaches and athletes, was validated.

To date, the validation of alternative protocols and shorter time trial efforts to estimate FTP is lacking (Sitko *et al.*, 2020). In conclusion, in their recent review of the literature on FTP, Mackey & Horner (2021) confirmed the 20 min TT to be a reliable test to determine FTP in trained to well-trained cyclists.

### 1.2.3 The use of FTP for cycling training prescription

Coggan developed seven power-based training levels / zones (Coggan, 2017). The methods behind the establishment of these levels are beyond the scope of this study, and can be found in the article by Coggan (2017). The table below (Table 1-1) gives a hypothetical example of the seven power levels according to FTP, the corresponding heart rates and the primary purpose for training at each level. Additionally, a brief summary of some of the main physiological adaptations expected to be associated with each level is also presented in the table.

**Table 1-1: Functional Threshold Power Training Zones (Allan & Coggan, 2006).**

| Coggan Power Zones | | | | | | |
|---|---|---|---|---|---|---|
| Zone | % of FTP | Power ranges (W) | Average heart rate | Heart rate (bpm) | Purpose of training at this level | Main expected physiological adaptations |
| Zone 1 | < 55% | < 184 | < 68% | < 118 | ACTIVE RECOVERY | n/a |
| Zone 2 | 56 - 75% | 188 to 251 | 69 - 83% | 97 to 144 | BASIC ENDURANCE TRAINING | Increased blood flow; increased number of mitochondria and mitochondrial enzymes; increased muscle glycogen storage; increased number of slow twitch (type I) muscle fibres. |
| Zone 3 | 76 - 90% | 255 to 302 | 84 - 94% | 146 to 164 | TEMPO TRAINING (RACE SIMULATION) | Increased muscle glycogen storage; increased number of mitochondria and mitochondrial enzymes; increased muscle capillarization; increase lactate threshold. |
| Zone 4 | 91 - 105% | 305 to 352 | 95 - 105% | 165 to 183 | DEVELOPMENT OF LACTATE THRESHOLD (LT) | Increased number of mitochondria, mitochondrial enzymes and enzyme efficiency; increase lactate buffering capacity and lactate tolerance. |
| Zone 5 | 106 - 120% | 355 to 402 | >106% | > 184 | $VO_{2max}$ TRAINING | Increased plasma volume, stroke volume, cardiac output and ultimately cardiovascular capacity (i.e. $VO_{2max}$). |
| Zone 6 | > 121% | > 405 | n/a | | ANAEROBIC CAPACITY | Inreased anaerobic capacity (lactate buffering capacity and lactate tolerance). |
| Zone 7 | n/a | maximal power | n/a | | NEUROMUSCULAR POWER | Increased neuromuscular power; hypertrophy of fast twitch (type II) muscle fibres; increased anaerobic energy stores (PCr, ATP). |

| FTP |
|---|
| 335 |
| $HR_{average}$ |
| 174 |

The physiological adaptations expected to occur in response to training at each intensity level was derived from fundamental exercise physiology principles and years of experience with power-based training (Coggan, 2017). Thus, the physiolgical validity of these training zones determined by a cyclist's FTP has not yet been verified by scientific research. This could be of great concern, due to athlete responsiveness to different training intensities being highly individualized (Iannetta *et al.*, 2020), potentiating the risk of under -or overtraining. In their book, "Training and Racing With a Power Meter", Allen *et al.*, (2019) provided a detailed discussion of developing highly individualized and specific training plans based on these power levels.

### 1.2.4 Relationship between FTP and metabolic parameters

Literature on the relationship between FTP and metabolic parameters will be discussed according to the protocol used to estimate FTP.

#### *1.2.4.1 Lactate Markers*

- **FTP determined as 95% of 20 min TT mean power output**

Borszcz *et al.*, (2019) reported that FTP and MLSS had a nearly perfect correlation (r = 0.91), and was not statistically significantly different (252 ± 26 W *vs.* 248 ± 25 W; $p > 0.05$) in a group of trained to well-trained cyclists (n = 15). In contrast, a significant difference ($p < 0.05$) between FTP (261 ± 45 W) and MLSS (243 ± 48 W) in a group of trained to well-trained cyclists (n = 18) have been reported by Inglis *et al.*, (2020). Similarly, Lillo-Beviá *et al.*, (2019) reported a significant difference between FTP and MLSS (262 ± 19 W *vs.* 250 ± 16 W; $p < 0.05$) in a group of trained cyclists and triathletes (n = 11). Additionally, it was recommended that  a stronger correction factor (91%) should be applied to the 20 min mean power output to be a valid predictor of the MLSS, rather than 95%. The discrepancy between the findings of the above mentioned studies could be attributed to the different warm-up protocols performed prior to the 20 min TT. It has been shown that the absence of higher intensity efforts during the warm-up preceding a time trial, such as the 5 min TT of the original FTP warm-up protocol (Allen *et al.*, 2019), a  higher mean power output during the time trial is achieved than when a time trial is included (Borszcz *et al.*, 2020; Tramontin *et al.*, 2022). Thus, it could be argued that the outcomes from Inglis *et al.*, (2020) and Lillo-Beviá *et al.*, (2019) may involve an overestimated FTP, due to the absence of higher intensity efforts in the warm-up. This would also clarify the reason why a stronger correction factor (91 %) was used in the study of Lillo-Beviá *et al.*, (2019).

When considering the power output associated with the lactate threshold determined by the $D_{max}$ method ($LT_{Dmax}$), Valenzuela *et al.*, (2018) concluded that FTP was not statistically significantly different from $LT_{Dmax}$ (240 ± 35 W *vs.* 246 ± 24 W, $p > 0.05$) and were strongly correlated ($r = 0.95$). Interestingly, these authors also reported that the relationship between FTP and $LT_{Dmax}$ seems to be affected by fitness status. They reported that recreational cyclists' FTP (n = 11) was significantly lower than their $LT_{Dmax}$ ($p = 0.0004$; ES = 0.81; LoA = −6.5 ± 8.3%) compared to trained cyclists (n = 9), where the difference between FTP and $LT_{Dmax}$ was small ($p = 0.2$; ES = 0.22; LoA = 2.1 ± 7.8%). Contrary to the findings of Valenzuela *et al.*, (2018), Jeffries *et al.*, (2019) reported that FTP (266 ± 42 W) and $LT_{Dmax}$ (221 ± 25 W) were significantly different in a group of trained to well trained cyclists (n = 18) ($p < 0.001$), as well as other lactate markers, namely $LT_{1.0}$, $LT_{mDmax}$, and IAT. They also found that OBLA (268 ± 30 W) and FTP (266 ± 42 W) were significantly correlated ($r = 0.88$, $p < 0.001$) with a trivial mean bias (~3 W). However, a large random error in the interindividual data (~100 W) questions their equivalence.

- **FTP determined as 90 % of 8 min TT mean power output**

The estimated FTP from the 8 min TT protocol (Carmichael & Rutberg, 2012) has been less extensively researched than the 20 min TT protocol, and conflicting findings question its validity as a true representation of FTP. Gavin *et al.*, (2012) was the first to evaluate the relationship between FTP estimated from the 8 min TT (Carmichael & Rutberg, 2012) with known lactate markers associated with cycling performance. They reported that FTP was not significantly different from the lactate threshold (LT) determined at a fixed blood lactate concentration of 4 $mmol.L^{-1}$ (OBLA) (301 ± 13 W *vs.* 293 ± 9 W; $p > 0.05$) in a group of trained cyclists (n = 7). Additionally, the estimated FTP was significantly higher than the LT where blood lactate rises by 1 $mmol.L^{-1}$ above baseline (i.e., $LT_{1.0}$) (301 ± 13 W *vs.* 264 ± 9 W; $p < 0.05$). In agreement to these authors' findings, Sanders *et al.*, (2017) reported that the estimated FTP was significantly different from $LT_{1.0}$ (341 ± 33 W *vs.* 300 ± 30 W; $p < 0.001$), however, contrary to Gavin *et al.*, (2012), found that the estimated FTP was also significantly different from OBLA (341 ± 33 W *vs.* 319 ± 25 W; $p < 0.01$) in a group of well trained cyclists (n = 19). Sanders *et al.*, (2017) further reported that the estimated FTP from Carmichael & Rutberg's (2012) proposed model is significantly different from other lactate thresholds as well, including $LT_{2.0}$ (278 ± 26 W; $p < 0.001$), $LT_{Dmax}$ (279 ± 20 W; $p < 0.001$) and $LT_{mDmax}$ (319 ± 29 W; $p < 0.001$). Perhaps the conflicting finding of Gavin *et al.*, (2012) can be attributed to their small study sample size (n = 7), compared to Sanders *et al.*, (2017) (n = 19). Another reason could be attributed to the age difference between participants in these two studies. Previous research has shown that time trial performance declines with age (Balmer *et al.*, 2008). Due to the much younger age (22 ± 2 years *vs.* 39 ± 3 yrs) of the participants in the study of Sanders *et al.*, (2017), their performance, i.e., FTP was higher relative to the performance of those recruited for the study of Gavin *et al.*, (2012) (341 ± 33 W *vs.* 301 ± 13 W). Even though this 8 min cycling test seems to be effective as a cycling performance and training monitoring tool (Klika, *et al.*, 2007), it cannot be assumed that this estimate of FTP (90% of the 8 min mean power output) is a true representation of a cyclist's FTP (Sitko *et al.*, 2020).

In summary, the current literature on the relationship between FTP and well-known lactate markers reveal conflicting findings. The most probable reasons being the influence of pacing ability during the time trails (Mackey & Horner, 2021), the age difference of participants (Balmer *et al.*, 2008) and the different exercise protocols and methods used to determine the various metabolic markers (Jones *et al.*, 2019; Poole *et al.*, 2021), as well as FTP (Sitko *et al.*, 2020). Essentially, as Mackey & Horner, (2021) points out in their scoping review on FTP, large limits of agreements exist between FTP from the different protocols and lactate markers, which suggests that FTP and these metabolic markers are not to be used interchangeably. Thus, the standardization of testing protocols is needed, and more research should be done to validate the relationhip of FTP with lactate markers.

#### *1.2.4.2 Oxygen Uptake Markers*

- **FTP determined as 95 % of 20 min TT mean power output**

Only one study could be found where the association between FTP and maximum oxygen uptake ($VO_{2max}$) was investigated. Denham *et al.*, (2020) reported that the relative FTP (2.6 ± 0.75 $W{\cdot}kg^{-1}$) and relative $VO_{2max}$ (46.8 ± 9.1 $W{\cdot}kg^{-1}.min^{-1}$) was positively and significantly correlated ($r = 0.84$, $p < 0.001$) in a heterogeneous cohort of cycle-trained and untrained individuals ($n = 40$). Additionally, $VO_{2max}$ explained 93.6% of variance in FTP. This would suggest that FTP is closely associated with the maximal capacity of oxidative processes for ATP production, i.e., the capacity of the aerobic energy system to produce ATP.

#### *1.2.4.3 Ventilatory Markers*

No studies explored the relationship between FTP and specific ventilatory markers, such as the first ventilatory threshold ($VT_1$), the second ventilatory threshold ($VT_2$), and the respiratory compensation point (RCP). Thus, more research is needed to establish what the relationship between different ventilatory responses and FTP is.

#### *1.2.4.4 Summary*

Overall, it is clear from the existing literature that research on the physiological and metabolic mechanisms underlying the FTP concept is scarce (Karsten, *et al.*, 2021). Given the popularity of FTP as a marker of training prescription among coaches and cyclists (Mackey & Horner, 2021) more research in this area is warranted.

### 1.2.5 Relationship between FTP with cycling performance

Despite FTP being a popular field test and benchmark of cycling performance (Allen *et al.*, 2019; Sitko *et al.*, 2020), research on its relationship with cycling performance and the predictive ability of FTP is limited.

#### *1.2.5.1 Maximal Exercise Capacity Test*

- **FTP determined as 95 % of 20 min TT mean power output**

Denham *et al.*, (2020) reported that the PPO achieved during a maximal incremental ramp test was significantly correlated with FTP ($r = 0.97$, $p < 0.001$) and that PPO explained 92.6% of the variance in FTP in a heterogenous group of cycle-trained and untrained ($n = 40$). The authors concluded that PPO from the ramp test accurately predicts FTP ($p < 0.001$). No other study has validated this exercise protocol for FTP estimation and this approach has also not yet been tested in trained to well-trained cyclists.

#### *1.2.5.2 Time Trial / Race Performance*

- **FTP determined as 95 % of 20 min TT mean power output**

Miller *et al.*, (2014) found that FTP significantly predicted performance in a 17.4 km Cross Country Olympic Mountain Bike (XCO-MTB) competitive race ($R^2 = 0.74$, $p < 0.001$) in well-trained male cyclists ($n = 11$). Likewise, Sørensen *et al.*, (2019) reported a significant relationship between FTP and performance time in a 47 km mountain bike race ($r = 0.74$, $p < 0.01$) in male, club level cyclists ($n = 11$). Morgan, *et al.*, (2019) also reported that FTP and 16.1 km road TT performance time was significantly and inversely correlated ($r = -0.87$, $p < 0.01$) for male, club level cyclists ($n = 12$).

- **FTP determined as 60 min TT mean power output**

Only one study evaluated the relationship between FTP, determined as the mean power output of a 60 min TT, and cycling time trial performance in a group of competitive, male cyclists. MacInnis *et al.*, (2019) compared the mean power output of a 4 min TT to the cyclist's 60 minute mean power output (i.e., FTP) and found a very strong correlation ($r = 0.95$, $p < 0.001$). They also noted that the riders achieved ~75% of their 4 min power output during the 60 min TT. Furthermore, the cyclists achieved 90% of their 20 min power output during the 60 min TT, implying that this correction factor is a more accurate estimate of the rider's FTP than the initially proposed 95 % (Allen *et al.*, 2019). These findings, however, are limited to a small sample size ($n = 8$) and should be validated in a larger sample.

#### *1.2.5.3 Summary*

Despite limited research and somewhat contradictory conclusions on the relationship of FTP with different metabolic parameters, it seems that this threshold does indeed have significant value for predicting endurance cycling performance. It is agreed that the need for protocol standardization in determining FTP and further physiological validation is needed (Mackey & Horner, 2021; Sitko *et al.*, 2020).

# 1.3 CRITICAL POWER

## 1.3.1 What is CP and where does it come from?

If we consider the limits to human exercise performance, we know that there is an inverse relationship between exercise intensity (e.g., a faster running speed, or a higher cycling power output) and duration of exercise. For example, a sprinter running at 25 km·h$^{-1}$ can only maintain this speed for a few seconds, while a marathon athlete, running at 14 km·h$^{-1}$ can maintain this pace for more than an hour. This dynamic relationship is captured in the critical power (CP) concept.

The CP concept was first described by Monod and Sherrer in 1965 and was defined as the hyperbolic relationship between work done (exercise intensity) and exercise duration (time). At this stage, CP was purely a mathematical concept (Jones *et al.*, 2010) based on the individual muscle function. Since then, this power-duration relationship have been extensively researched and extended to whole-body exercise. The review articles by Jones & Vanhatalo (2017); Morton (2006) and Vanhatalo *et al.*, (2011) provide an in depth historical, theoretical, physiological, and mathematical background on the CP concept.

Currently it is understood that CP represents the highest intensity of exercise at which a metabolic steady-state can be maintained (Jones *et al.*, 2019; Poole *et al.*, 2021). At this exercise intensity, aerobic and anaerobic energy systems work in a coordinated fashion (Jones *et al.*, 2010; Vanhatalo *et al.*, 2011), while unique physiological responses is observed above and below this critical exercise intensity (Jones *et al.*, 2019; Jones & Vanhatalo, 2017). *Above* this critical exercise intensity the anaerobic energy system contribution to ATP production increases to such an extent that a metabolic steady-state can no longer be maintained, and inevitably leads to accelerated fatigue and exercise termination (Jones *et al.*, 2011; Whipp, *et al.*, 2005). Fatigue at exercise intensities *above* CP is attributed to specific muscle metabolic -and neuromuscular behaviors resulting in reduced muscular excitability and increased metabolic stress, collectively leading to exercise termination (Black *et al.*, 2017). The metabolic behaviors associated with fatigue *above* CP include low muscle Phosphocreatine (PCr), ATP and pH concentrations, high blood lactate concentrations, the attainment of $VO_{2max}$, and a short time-to-exhaustion anywhere between 2 - 20 minutes (Black *et al.*, 2017; Jones, *et* *al.*, 2008). These metabolic paramaters have been shown to remain stable at intensities *below* CP (Vanhatalo *et al.*, 2016). The neuromuscular behaviors associated with fatigue at intensities *above* CP have been described as reduced muscular excitability and neural drive (Black *et al.*, 2017). Although CP, in theory, presents the exercise intensity that can be sustained for a prolonged period of time, as per its original definition (Monod & Scherrer, 1965), it would be unwise to suggest that CP can be sustained for any specific duration of exercise, as several integrated fatigue mechanisms contribute to the limit of exercise tolerance (Ament *et al.*, 2009; Brickley *et al.*, 2002; Fitts 1994; Poole *et al.*, 2016; Thomas *et al.*, 2014).

An integral component of the CP concept is W-prime (W') which is calculated as the curvature constant of the hyperbolic power-time curve (Vanhatalo *et al.*, 2011). W' represents the magnitude of work (kJ) available during exercise intensities *above* CP (Poole *et al.*, 2016; Skiba *et al.*, 2015; Vanhatalo *et al.*, 2011), which is principally derived from anaerobic energy sources. Even though it is understood that the magnitude of W' relates to the "distance" between CP and $VO_{2max}$ (Jones *et al.*, 2010), the exact physiological mechanisms underlying this parameter remains uncertain (Chorley & Lamb, 2020). What is known, is that W' constitutes the work rates exceeding the CP threshold that will lead to: 1) the attainment of $VO_{2max}$ if the intensity can be sustained for sufficiently long (Poole *et al.*, 2016), and 2) the depletion of fuel stores (muscle- and liver -glycogen and muscle PCr) and/or 3) the accumulation of intramuscular metabolites (e.g., $H^+$-ions and $P_i$) (Jones *et al.*, 2008; Skiba *et al.*, 2012; Skiba *et al.*, 2015).

Several mathematical models (Jones *et al.*, 2010; Morton, 2006) were developed where CP and W' are used to estimate / predict the time for which exercise can be sustained at given intensities *above* CP. These models do not apply to exercise intensities *below* CP (Vanhatalo *et al.*, 2011). A fundamental phenomenon to understand regarding the CP concept, is that both CP and W' rely on oxygen availability (Broxterman *et al.*, 2015; Ferretti 2015; Jones *et al.*, 2010), thus, W' should not be interpreted as representing a fixed, purely anaerobic capacity (Tsai, 2015). It has been argued that CP alone provides information on the highest sustainable oxidative metabolic rate during heavy-intensity exercise, while W' and CP collectively allows for the prediction of exercise tolerance during severe-intensity exercise (Jones *et al.*, 2010; Skiba *et al.*, 2012; Vanhatalo *et al.*, 2011), i.e., exercise intensities *above* CP.

The notion that CP represents an exercise intensity that could be sustained for a "very long time" has been refuted (Black *et al.*, 2022; Burnley, 2022; Pethick, Winter & Burnley, 2020). CP is understood to represent a unique threshold depicting a physiological phase transition between metabolic steady-state *vs.* non-steady-state behaviors (Pethick *et al.*, 2020). It is therefore advocated as being the "gold standard" threshold for demarcating the transition from heavy-intensity -to severe-intensity exercise (Jones *et al.*, 2019). CP as a threshold is unique when compared to the more traditional metabolic thresholds (i.e., lactate thresholds, e.g., MLSS, $LT_{1.0}$, OBLA; ventilatory thresholds; RCP; $VO_{2max}$), as it represents a more holistic, whole-body metabolic steady-state, rather than a steady-state limited to a singular metabolic marker (Jones *et al.*, 2019; Poole *et al.*, 2021). CP can therefore also be regarded as a functional threshold, as it is purely based on the measurement of mechanical work done and exercise tolerance.

### 1.3.2 Methods to determine CP

CP is traditionally determined by multiple (3 - 5) tests-to-exhaustion at different constant work rates and performed on different days (Brickley *et al.*, 2002; Mattioni *et al.*, 2016; Pringle & Jones, 2002; Vanhatalo *et al.*, 2007). The power outputs are then plotted against time (Fig 1-2) in a hyperbolic fashion, where the power asymptote of the graph represents CP and the curvature constant represents W', quantified in kJ (Morton 2006; Poole *et al.*, 2016; Skiba *et al.*, 2015; Vanhatalo *et al.*, 2011).

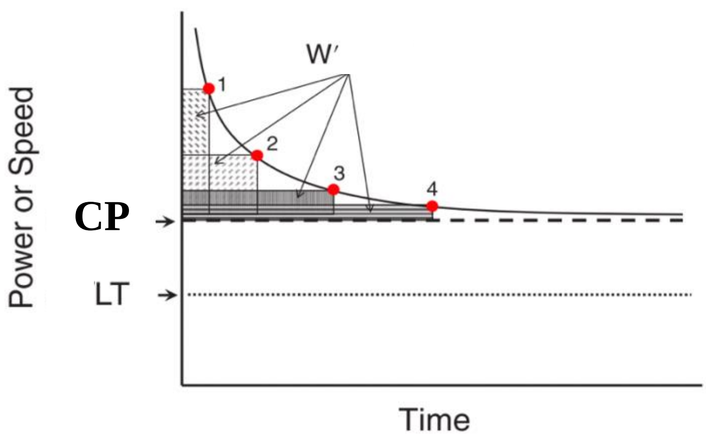



**Figure 1-3: CP determined from multiple constant-load exercise tests**

(modified from Poole *et al*., 2021)

Burnley *et al.*, (2006) explored the novel idea of using a single exercise test to determine CP (Fig 1-3). They reported that the power output during a 3-min all-out cycling test tends to decline to a power output associated with a steady state of key metabolic parameters (e.g. blood lactate and $VO_2$), indicating a metabolic steady state. These authors also noted that the decline in power output during the final 60 s of the test was insignificant, a reduction of only 5 W was observed (95% confidence limits 11, -1 W; $p > 0.001$), thus, concluding that the final 30 s of a 3-min all-out cycling test represents a maximal steady state, i.e., CP. This much simpler and quicker method has been further explored and shown to be valid and reliable for determining CP (Broxterman *et al.*, 2015; Johnson *et al.*, 2011; Vanhatalo *et al.*, 2007). CP is calculated as the mean power output of the final 30 s of a 3-min all-out test (Vanhatalo *et al.*, 2007) (Fig 1-3). This single 3-min testing protocol offers an advantageous alternative to traditional CP protocols which require numerous cycling tests and visits to an exercise physiology laboratory (Jones *et al.*, 2017; Vanhatalo *et al.*, 2008a; Vanhatalo *et al.*, 2011).

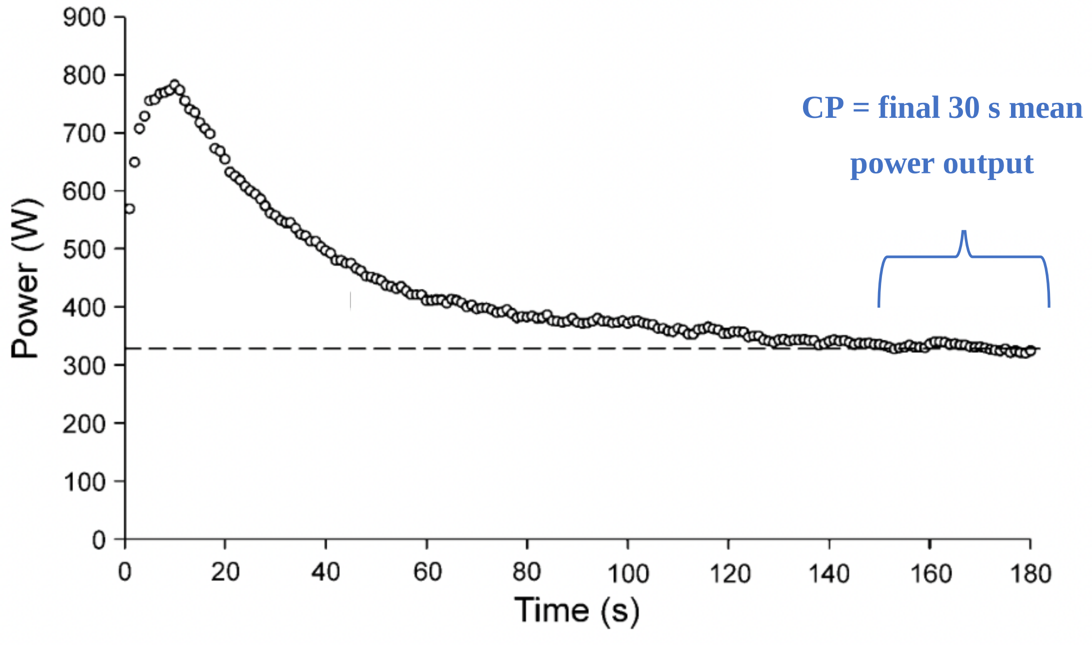



**Figure 1-4: Critical Power determined from the 3-min all-out protocol**
(modified from Vanhatalo *et al.*, 2007)

### 1.3.3 Relationship between CP and metabolic parameters

The magnitude of different exercise testing protocols and methodologies being used in the literature for measuring endurance performance variables inevitably causes inconsistent and inconclusive interpretations of cycling endurance performance. Such is the case with the current literature on the relationship between CP and cycling performance, where each existing study used different methods to determine and describe CP. For the purpose of this study, the findings from studies that utilized the 3-min all-out protocol (Vanhatalo *et al.*, 2007) was reported in this section.

#### *1.3.3.1 Lactate Markers*

Maturana *et al.*, (2016) reported that the power output associated with the MLSS was significantly lower than CP (233 ± 41 W *vs.* 250 ± 51 W; $p < 0.05$), in a heterogenous group of cyclists ranging from recreational to elite level (n = 13). They also reported wide limits of agreement (LoA) between the CP estimated from the 3-min all-out test, (-29 W to 62 W) compared to CP from five TTE trials (-7 W to 48 W). Due to these wide LoA and the disagreement with the power output at MLSS, the ability of CP to estimate the maximal steady state was questioned. Francis *et al.*, (2010) reported that CP (273 ± 52 W) was strongly correlated (r = 0.79 - 0.85), but significantly higher than the power outputs at OBLA and $LT_1$ (235 ± 54 W, 208 ± 45 W; $p < 0.05$) in a group of competitive road cyclists (n = 16). Based on their findings, Francis *et al.*, (2010) showed that CP could be used to establish exercise intensity zones, based on the distribution of power outputs of $LT_1$, OBLA and CP (refer to their article for a schematic illustration). A limitation to this study was that a modified version of the 3-min all-out test was used to estimate CP, where subjects could change their gear ratios throughout the test. This method questions the study outcomes with reference to CP, i.e., whether true CP was measured.

Thus, the literature suggests that CP derived from the 3-min all-out test is detected at a higher exercise intensity (power output) than the lactate thresholds (MLSS, OBLA and $LT_1$). Ultimately, a greater contribution of anaerobic energy sources is related to intensities closely associated with CP, compared to primary aerobic ATP production with lower intensities, such as intensities associated with $LT_1$.

#### *1.3.3.2 Oxygen Utilization Markers*

Burnley *et al.*, (2006) were the first to evaluate the use of the 3-min all-out protocol to establish $VO_{2peak}$ and estimate the maximal steady state. They reported that the $VO_{2peak}$ from the 3-min all-out test and the $VO_{2peak}$ determined from a cycling ramp test were not significantly different (3.78 ± 0.7 $ml \cdot kg^{-1} \cdot min^{-1}$ *vs.* 3.84 ± 0.79 $ml \cdot kg^{-1} \cdot min^{-1}$; $p = 0.75$) in a group of recreationally active individuals ($n = 11$). Furthermore, they found that a TTE trial at an intensity equal to 15 W *below* CP resulted in no significant change in blood lactate concentration and $VO_2$ levels, however, at an intensity equal to 15 W *above* CP, blood lactate and $VO_2$ response profiles rose exponentially until exhaustion after 13 ± 7 min. The authors thus concluded that CP indicates the maximal metabolic steady state for endurance exercise. Nicolò, *et al.*, (2017) compared $VO_2$ parameters associated with an incremental ramp test, the 3-min all-out test and a 10-min cycling TT, in an effort to verify the accuracy of CP to predict cycling performance in the severe-intensity domain. Ten well-trained, male cyclists were recruited. They reported that the $VO_{2peak}$ values obtained from the maximal incremental ramp test, the 3-min all-out test and the 10-min TT were not significantly different (66 ± 9 $mL \cdot kg^{\cdot -1} \cdot min^{-1}$ *vs.* 65 ± 6 $mL \cdot kg^{\cdot -1} \cdot min^{-1}$ *vs.* 65 ± 7 $mL \cdot kg^{\cdot -1} \cdot min^{-1}$; $p > 0.05$).

Collectively, the literature on the relationship between CP and $VO_2$ parameters suggest that CP is associated with severe exercise intensities, i.e., exercise intensities where the aerobic energy system is near / at maximum operating capacity, increasing the reliance of anaerobic energy sources (Jones *et al.*, 2019).

#### *1.3.3.3 Ventilatory Markers*

There are limited studies on the relationship between CP and the ventilatory thresholds. Francis *et al.*, (2010) reported that the CP of 16 competitive cyclists were strongly correlated with, but significantly greater than the power output associated with $VT_1$ (273 ± 52 W *vs.* 232 ± 64 W; $p < 0.05$). Similarly, Bergstrom *et al.*, (2013) reported that the power output associated with $VT_1$ and the gaseous exchange threshold (GET) (145 ± 37 W and 139 ± 37 W, respectively) were significantly lower than CP (187 ± 47 W) ($p < 0.05$) in a group of moderately trained cyclists ($n = 28$). These authors also reported that CP and RCP were not significantly different (187 ± 47 W *vs.* 190 ± 49 W; $p > 0.05$). The authors from the latter findings concluded that RCP and CP are associated with different mechanisms of fatigue compared to GET and $VT_1$, due to the different intensities associated with the thresholds, i.e., that CP and RCP demarcate the heavy from severe exercise intensity domain, compared to GET and $VT_1$ demarcating the moderate -and heavy-intensity domain.

#### *1.3.3.4 Summary*

Collectively, it has been established that CP occurs at a higher intensity than $VT_1$ and GET, MLSS, OBLA and $LT_1$, and is closely associated with the RCP. Additionally, CP is associated with stable blood lactate and $VO_2$ response profiles at intensities below CP, but non-stable response profiles at intensities above CP.

### 1.3.4 Relationship between CP and cycling performance

The relationship between CP determined from the 3-min all-out protocol and cycling TT performance has not been much explored. Only the findings from studies that utilized the 3-min all-out protocol is reported in this section.

#### *1.3.4.1 Time Trial / Race Performance*

Black *et al.*, (2014) was the first to evaluate the efficacy of the 3-min all-out CP test in predicting road cycling time trial (TT) performance. They reported that CP (309 ± 34 W) was significantly correlated with 16.1-km TT performance (27.1 ± 1.2 min; $r = -0.83$, $p < 0.01$) in male, club-level cyclists ($n = 10$). Nicolò *et al.*, (2017) reported that the mean power output of a 10-min TT and CP in a group of well-trained male cyclists (n=10), was not significantly different (351 ± 53 W *vs.* 347 ± 30 W; $p > 0.05$).

#### *1.3.4.2 Summary*

Collectively, from these two studies, it seems that CP is significantly related to cycling performance of short distance/duration time trials, i.e., 16.1 km and 10-min.

# 1.4 RELATIONSHIP BETWEEN FTP AND CP

To the researcher's knowledge, no previous study examined the relationship between CP determine from the 3-min all-out protocol and FTP. The studies discussed in this section all utilized different protocols to estimate CP, i.e., multiple (3 - 5) constant load cycling tests performed at intensities determined by different means, e.g., self-paced TT or intensities according to a given percentage of a cyclist's PPO. Additionally, the duration of the trials across the studies also differed, ranging from 3 - 15 minutes per test. For all these studies, FTP was estimated as 95 % of 20-min TT mean power output.

Karsten *et al.*, (2021) reported that a significant correlation exists between CP and FTP ($r = 0.969$; $p < 0.001$) in a group of trained cyclists and triathletes ($n = 17$). The authors examined the relationship between FTP and CP estimated from three different models, (i.e., the linear power output *vs.* inverse of time model; the linear work *vs.* time model; and the hyperbolic power output *vs.* time model). Collectively, they concluded that there was a 91.7 % chance that CP (256 ± 50 W) was higher than FTP (249 ± 44 W), and that the relatively large limits of agreement (LoA) (-19 to 33 W) suggest that FTP and CP should not be used interchangeably. Another study revealed that CP was significantly higher than FTP (282 ± 53 W *vs*. 266 ± 55 W; $p < 0.001$) in a group of highly-trained athletes (McGrath *et al.*, 2021). Morgan *et al.*, (2019) reported that FTP and CP in a group of competitive, male cyclists ($n = 12$) were not significantly different (278 ± 42 W *vs.* 275 ± 42 W; $p > 0.05$), however, the LoA (30 to -36 W) were too large to consider FTP and CP interchangeable.

In a recent review article (Mackey & Horner, 2021) it was concluded that researchers agree that FTP and CP are both correlated to cycling performance of trained cyclists, but that large LoA between these two parameters indicate that they are not interchangeable. Moreover, when compared to FTP, the physiological clarity around the CP concept is much more established, as it has been extensively researched for decades (Bassett, 2002; Hill, 1993; Jones *et al.*, 2019; Jones, Vanhatalo, Burnley, *et al.*, 2010b; Morton, 2006). Additionally, CP has been advocated as the "gold standard" parameter representing the maximal metabolic steady state and depicting the transition from heavy-intensity to severe-intensity exercise (Jones *et al.*, 2019; Mackey & Horner, 2021; Poole *et al.*, 2021). Unlike CP, the physiological nature of FTP seems arbitrary due to the lack of evidence of the physiological underpinnings of this threshold (Mackey &

Horner, 2021). Mackey & Horner (2021) reiterated that no research has been published on the physiological responses at intensities above and below FTP, thus, its physiological underpinnings are unconfirmed. It could be argued that FTP is a threshold situated well within the heavy-intensity domain (Allen *et al.*, 2019; Borszcz *et al.*, 2018, 2019), whereas CP is regarded the "gold standard" measure for indicating the transition from the heavy to severe-intensity domain (Jones *et al.*, 2019) (Fig 1-4).

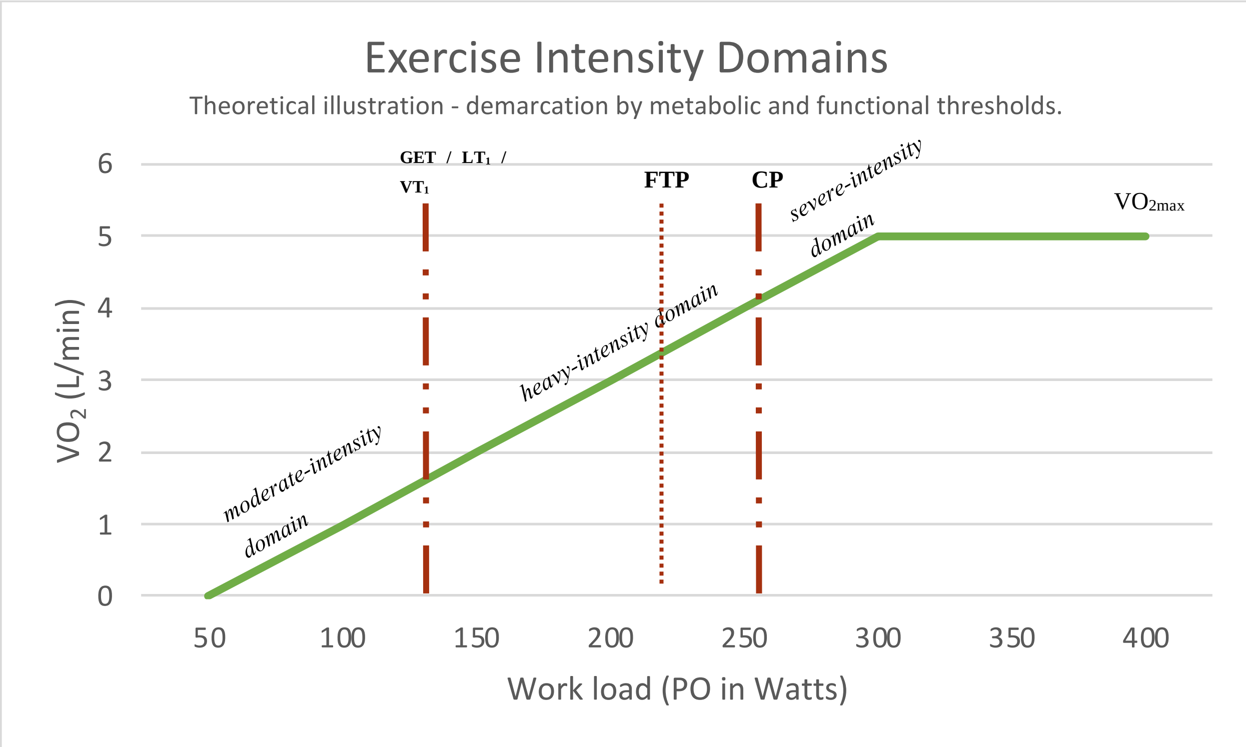



**Figure 1-5: Theoretical illustration of Functional Threshold Power and Critical Power on the exercise intensity continuum.**

# Chapter 2 PROBLEM STATMENT

The existing literature discussed in the previous sections, ascertains that both functional threshold power (FTP) and critical power (CP) represent thresholds that are associated with high-intensity endurance exercise (> $LT_{1.0}$ ; ≥ MLSS; ≥ OBLA) (Barranco-Gil *et al.*, 2020; McGrath *et al.*, 2021; Poole *et al.*, 2021). FTP is essentially determined by a time trial over a preset time period, ranging from 8 to 60 minutes. The definition of "steady state" underlying FTP is primarily built around blood lactate parameters, i.e., the intensity where a blood lactate steady state is achievable (i.e., the MLSS). It is well known that endurance performance is a vastly complex and integrated system of cardio-respiratory and metabolic control (Ferretti, 2015) and that lactate is not the only factor involved in a metabolic steady state (Jones *et al.*, 2019; Poole *et al.*, 2021). Additionally , an athlete's pacing strategy, mental fatigue and lactate tolerance also contribute to endurance exercise performance (Marcora *et al*., 2010; Skorski & Abbiss, 2017).

A limitation of the methodology for determining FTP, i.e., performing a time trial, is that the competitive level and experience of the cyclist will largely determine the reliability of the outcome (Hibbert *et al.*, 2017) due to differences in pacing ability. A further concern that surfaced from the literature is that the correction factor proposed by (Allen *et al.*, 2019) appears arbitrary, and should probably be reconsidered (Lillo-Beviá *et al.*, 2019; MacInnis *et al.*, 2019; Mackey *et al.*, 2021). Due to the popular use of FTP to measure and monitor cycling performance and to prescribe training zones, it is of fundamental importance to ensure that an accurate correction factor is used when using time trials shorter than the originally proposed 60 -or 20 min durations (Carmichael & Rutberg, 2017) or alternative testing protocols (Denham *et al*., 2020) to estimate FTP. By under -or over estimating a rider's FTP, the intensity and training stress scores (Allen *et al.*, 2019) of specific training sessions might be incorrect , and poses the risk of the cyclist either under-training or over-training.

Being a functional threshold, i.e., an objective measure of work done (power output) and exercise duration, additional to not relying on numerous, expensive laboratory visits and equipment, FTP is a more convenient and more readily accessible threshold to use as a training tool compared to more traditional metabolic thresholds. It is therefore essential that the underlying physiology, and the methods through which FTP should be determined, is confirmed and agreed upon. Nevertheless, the current literature suggest that FTP is a valid indicator of a cyclists endurance performance ability, which can be a powerful tool to predict cycling performance in the field.

Despite CP not being a new phenomenon, there is limited research on the relationship between CP estimated from the 3-min all-out protocol and cycling performance. The current literature reveals that CP closely associates with metabolic parameters known to be associated with high intensity exercise (e.g., RCP, $VO_{2peak}$) and is located at a higher power output than lactate thresholds (e.g., $LT_{1.0}$, MLSS, OBLA). Additionally, CP is closely associated with cycling TT performances of short distance / duration (16.1 km and 10 min) time trials. The association of CP from the 3-min all-out protocol and cycling endurance performance for longer distances, i.e., > 16.1 km, is yet to be established. What can be concluded from the literature is that CP is related to cycling performance at the higher end of the exercise intensity continuum, i.e., intensities associated with the higher end of the heavy-intensity exercise domain and the lower end of the severe-intensity exercise domain (Chorley & Lamb, 2020; Jones *et al.*, 2019).

As mentioned previously, exercise intensities above and below CP are characterized by distinct physiological responses, such as non-steady and steady state oxidative metabolism. In other words, CP is an indicator of the transition from the heavy-intensity to severe-intensity exercise domain. FTP in comparison, is a power measure situated towards the upper-end of the heavy-intensity domain. When considering cycling time trials, due to the greater average exercise intensity during shorter (e.g., 20 km) cycling TTs (Bentley *et al.*, 2001; McNaughton *et al.*, 2006; Morgan *et al.*, 2019; Padilla *et al.*, 2000), a greater portion of the exercise is likely to be performed in the severe-intensity domain (Jones *et al.*, 2019; Morgan *et al.*, 2019). This is in contrast to longer time trials (e.g., 40 km) which are predominantly performed in the heavy-intensity domain. Therefore, it could be hypothesized that both time trial distances would show strong correlations with both thresholds, but that the shorter 20 km time trial would be more strongly associated with CP and the longer 40 km time trial with FTP. Additionally, TT20 would occur at a higher fractional percentage of CP compared to the longer 40 km time trial. Likewise, TT20 would occur at a higher percentage relative to FTP than TT40. Both FTP and CP, being functional thresholds, are probably more comprehensive descriptors of an athlete's cycling performance capabilities, as endurance performance cannot be limited to the functioning of a singular metabolic parameter, such as lactate (Jones *et al.*, 2019). Both thresholds are derived from mechanical work done (i.e., power output) and exercise tolerance (Allen *et al.*, 2019; Jones *et al.*, 2017; Jones *et al.*, 2010) and are thus more accessible to coaches and athletes at all levels. Moreover, knowledge of which functional threshold is best correlated with longer (i.e., 40 km) and shorter (i.e., 20 km) cycling performance, would guide coaches, athletes, and practitioners in using the most appropriate cycling test to evaluate and monitor a rider's cycling performance capacity.

## 2.1 Purpose, Aims and Objectives

### 2.1.1 Purpose of the Study

To the researcher's knowledge, no previous study evaluated the relationship of CP estimated from the 3-min all-out protocol, FTP and cycling performance of different distances, i.e., 20 km and 40 km. Therefore, the purpose of this study was to evaluate the functional thresholds (FTP and CP) and its association with cycling performance over two distances, namely 20 km and 40 km.

### 2.1.2 Research Aims

#### *2.1.2.1 Primary Aims*

- To examine the relationship between CP and FTP with known endurance performance markers, $VO_{2max}$ and PPO.
- To determine the correlation of CP with cycling performance over 20 km (TT20) and 40 km (TT40) cycling time trial.
- To determine the correlation of FTP with cycling performance over a 20 km (TT20) and 40 km (TT40) cycling time trial.
- To examine which threshold (CP or FTP) correlates strongest with the short (TT20) and long (TT40) time trial distance, respectively.

#### *2.1.2.2 Secondary Aim*

- To determine the difference between the power outputs of FTP, CP and PPO on the exercise intensity continuum.

### 2.1.3 Objectives

1. To determine $VO_{2max}$ and PPO during a maximal ramp incremental test-to-exhaustion.
2. To determine the power output estimate of CP during a 3-min all-out test.
3. To estimate FTP from a 20-min TT.
4. To determine mean power output and time to completion from 20 km and 40 km time trials.

# Chapter 3 METHODOLOGY

## 3.1 STUDY DESIGN

This study followed a cross-sectional descriptive design. Cyclists' functional threshold power (FTP), critical power (CP), peak power output (PPO), performance time and mean power output for a laboratory-based 20 km -and 40 km time trial (TT20, TT40, respectively), were determined over a period of days. Metabolic data (i.e., $VO_{2max}$) was only measured during the initial two incremental ramp tests for descriptive purposes.

A snowball sampling method was used to recruit the volunteers. This method was chosen due to the various groups of cyclists, particularly mountain bikers, in the Stellenbosch area. The study was advertised by means of a flyer (Appendix A) on social media platforms (Facebook™, Instagram™ and Whatsapp™). Interested cyclists contacted the researcher personally and were screened via WhatsApp, after which those meeting the inclusion criteria were invited to their first laboratory visit.

## 3.2 ETHICAL ASPECTS

The study was approved by the Health Research Ethics Committee (HREC) at Stellenbosch University (S21/09/176). All testing and laboratory procedures were performed in accordance with the Declaration of Helsinki.

## 3.3 PARTICIPANTS

A priori sample size estimation was determined with G*Power 3 software (Faul *et al.*, 2007) based on the results of Denham *et al.* (2020). It was calculated that 12 participants would be sufficient to detect a statistically significant difference between threshold power outputs (effect size = 1.0, 95% power, and 5% level of significance). It was therefore decided to recruit 15 volunteers to make provision for a 20% drop-out rate. Thus, fifteen (n=15) trained to well-trained mountain bikers, 8 men and 5 women, were recruited.

### 3.3.1 Inclusion Criteria

To participate in this study, it was required that individuals:

- are between 19 and 55 years of age;
- have at least one year of cycling experience;
- primarily mountain bike as an exercise activity;
- perform at least 6 hours of cycling training per week (over the last 6 months prior to study participation).

### 3.3.2 Exclusion Criteria

Participants were excluded from the study if they:

- suffered a musculoskeletal injury (over the past 6 months or during the testing period) which would constrain their performance during the exercise tests;
- made use of pharmaceutical drugs and/or ergogenic aids that would affect energy metabolism or any measurements of physical performance;
- violated one or more of the pre-test requirements (see section 3.5.1)
- answered "yes" to any of the questions from the ACSM Medical Screening Questionnaire (Appendix B).

## 3.4 STUDY OVERVIEW

Exercise testing took place in the Sport Physiology Laboratory of the Department of Sport Science, University of Stellenbosch.

A document outlining the study procedures and including informed consent forms (Appendix C) was sent to each participant prior to their first visit, via WhatsApp or email, for the participant to read through. Upon their first visit, the researcher ensured a thorough understanding of the study procedures, expectations, and informed consent by the participant, and answered questions as needed. Thereafter, the participant was asked to sign the informed consent forms. To allow for a familiar and comfortable cycling posture during exercise testing, which is known to affect energy cost (Gnehm, *et al.*, 1997), joint ranges of motion and muscle activation patterns (Sanderson *et al.*, 2009), participants brought their own training bikes (road or TT bikes) to the laboratory which were mounted to the Cyclus2 ergometer (RBM elektronik-automation, Leipzig, Germany). The set-up dimensions were recorded and replicated for each cycling test. Upon the first visit, body composition measurements were taken, and a familiarization trial of the ramp incremental test and 3-min all-out test was performed.

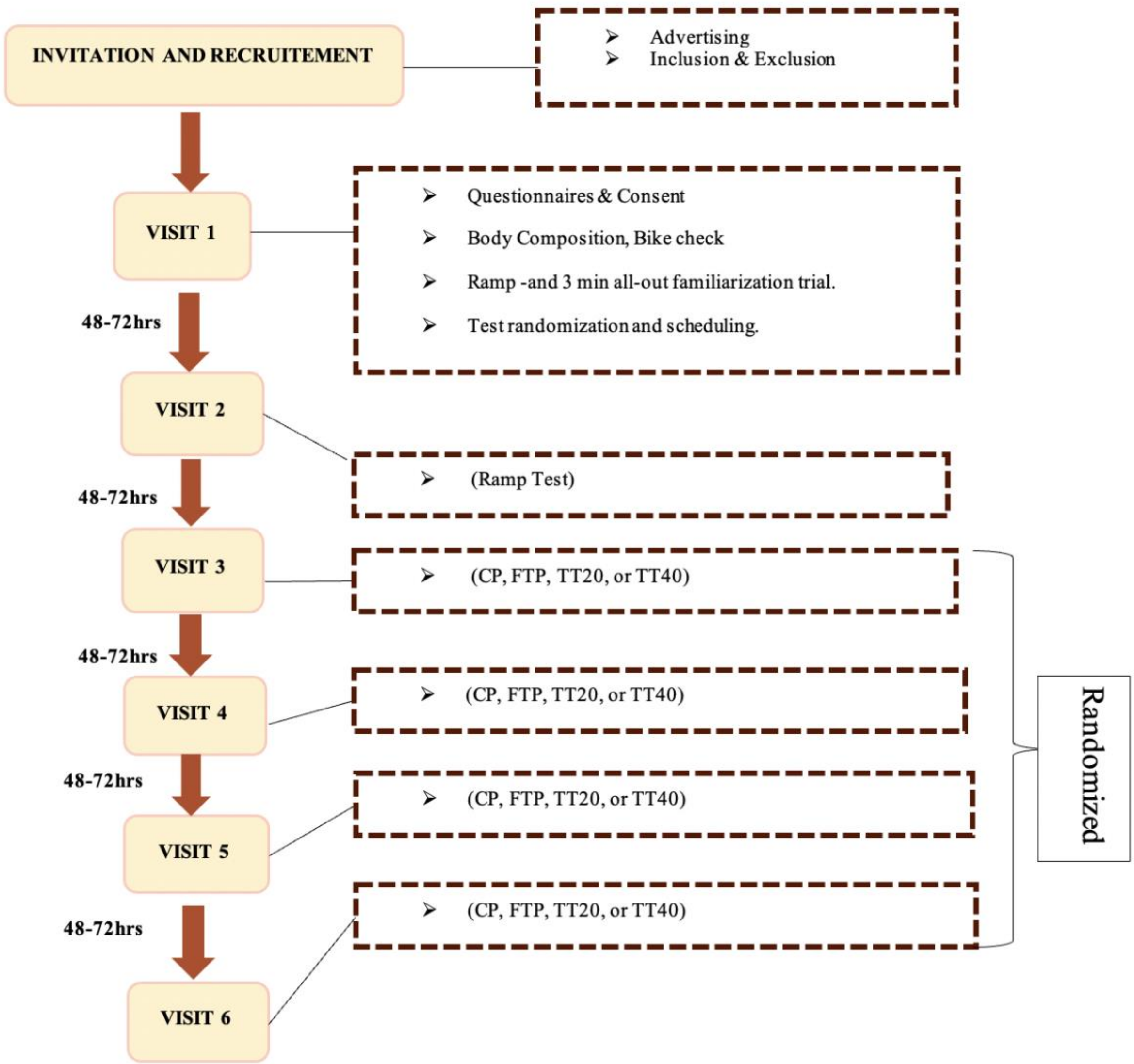



**Figure 3-1: Illustration of the Study Procedures**

Visits 1 and 2 were the same for all participants and included an incremental ramp test during which a Cosmed Quark CPET (Rome, Italy) metabolic analyzer was used to collect metabolic data for descriptive purposes (i.e., $VO_{2max}$). Due to technical difficulties, an alternative metabolic analyzer, the Cosmed K5 (Rome, Italy) portable system, was used during the incremental ramp tests of three participants. Exercise tests during visits 3 - 6 were randomized for each participant using an online randomizer (https://wwW·randomizer.org). The tests included: a) a 3 min all-out test (CP); b) a 20 min FTP; c) a 20 km time trial (TT20) and d) a 40 km time trial (TT40). The randomization was done in such a manner that the two TTs were not performed within the same week to allow for complete recovery. Participants were informed about the cycling test which they will be performing prior to their visit. Due to the varying duration of the different tests, participants were allowed to request a change in their cycling test sequence if time was a constraint on a particular day.

## 3.5 TESTING AND MEASUREMENTS

All testing was conducted in a well-controlled laboratory environment, with relative humidity at 54 ± 5.4% and ambient temperature at 21°C ± 1.5.

A 10 - min warmup was conducted before every test, where each participant was allowed to cycle at their preferred cadence and torque. A 5-min stationery rest on the bike commenced, during which participants were allowed to drink water and ask questions regarding the test. Participants were not blinded to their power output and heart rate (Borg *et al.*, 2020; Brown & Bray, 2019) and were able to view elapsed time / distance in order to allow for individualized pacing (Miller *et al.*, 2014; Morgan *et al.*, 2019). Participants were allowed water *ad libitum* during the 20-min FTP, TT20 and TT40 cycling tests. Verbal encouragement was given during the ramp and 3 min all-out tests by the researcher, however, no verbal encouragement was given during the FTP, TT20 and TT40 trials to prevent interference with the cyclist's pacing strategy. At test termination, the researcher recorded participants' final RPE score (Appendix D).

### 3.5.1 Pre-exercise Test Requirements

All testing were conducted at the same time of day for each participant. To standardize the participant's metabolic state during the testing sessions, participants were sent the following checklist prior to their visit:

- to eat their last meal at least three hours prior to testing;
- to avoid caffeine-containing drinks and alcohol ingestion at least 12 hours before testing;
- to avoid vigorous activities – RPE above 12 on the Borg scale (Appendix D) - or any unaccustomed exercise at least 24 hours before testing;
- to stay well hydrated prior to testing.

### 3.5.2 Health Screening Questionnaire (Appendix B)

The ACSM Health Screening Questionnaire (2020) was used to identify any contraindications that may warrant the participant's exclusion from the study. The ACSM questionnaire is in the public domain and was specifically developed for research laboratories such as the Sport Physiology Laboratory (Riebe *et al.*, 2018).

### 3.5.3 Participant Training Questionnaire (Appendix E)

The participant training questionnaire was self-developed by the researcher and asked questions related to the participant's frequency, duration, and intensity of cycling exercise. It further posed questions related to their experience in cycling.

### 3.5.4 Anthropometric Measures

Participant's height was measured using the stretch stature method, with a sliding stadiometer (Seca, Germany). The participants were asked to stand barefoot on the scale with their heels together. The heels, buttocks and upper part of the back were to touch the scale, with the head in a Frankfort position. This is when the orbital (lower edge of the eye socket) and the tragion (the notch superior to the tragus of the ear) are horizontally aligned. The participant were asked to take a deep breath as the researcher placed the head-board firmly on the vertex, compressing the hair as much as possible. The measurement was taken to the nearest 0.1 cm.

Body weight was measured using a calibrated electronic scale (UWE BW-150, 1997 model Brisbane Australia) and recorded to the nearest 0.1 kg.

### 3.5.5 Body Composition Measurements

A BodyMetrix BX2000 ultrasound device (Hosand Technologies srl, Verbania) was used to determine the participant's body composition. The individual's height and body weight were entered into the computer software. On the Bodyview Software (IntelaMetrix, Concord, CA, USA), the three-sites (Pollock) for skinfold measurements were selected, whereafter the sights were marked on the left side of the participant's body using a non-permanent marker. The BodyMetrix$^{TM}$ software estimated percentage body fat, fat mass and fat free mass.

The three-sites measured for men and women were different, according to the software system. For men participants, skinfold measures of the thigh, axilla and chest were taken. For women, skinfold measures of the waist, hip and triceps were taken.

The sites were defined as follows:

- Thigh: the midpoint of the anterior thigh between the hip joint and the knee.
- Axilla: located below the armpit and level with the bottom of the sternum.
- Chest: halfway between the shoulder and the nipple.
- Waist: located 5 cm to the side of the belly button.
- Hip (Suprailiac): located 5 cm above the anterior side tip of the hip bone.
- Triceps: the midpoint of the posterior upper arm, between the elbow and the shoulder.

A droplet of ultrasound gel was applied to the device and reapplied during the assessment if necessary. The BodyMetrixTM probe was placed on each anatomical site and scanned for 3-5 s. The BodyMetrix device generates an ultrasound signal travelling through the tissue and records the localized fat layer and muscle layer thickness (mm). Each site was measured 2 - 3 times for accuracy. If the first and second measurement did not differ by more than 1 mm, the second measurement was noted. If the difference was larger, a third measurement was taken and noted, provided that two measurements were within 1 mm.

### 3.5.6 Ramp Incremental Test

The Ramp Incremental Test was performed to obtain Peak Power Output (PPO) (Watts), $VO_{2max}$, $HR_{max}$ and rider preferred cadence (rpm). Ratings of perceived exertion (RPE) were also recorded after the test. The test started with a 3-min baseline phase at 100 W (women) and 150 W (men). Thereafter the load increased by 1 W every 3 s (a total of 20 $W{\cdot}min^{-1}$) until volitional exhaustion (Denham, *et al.*, 2020). Participants were asked to maintain a cadence between 80 - 100 rpm throughout the test. The test was aborted if the cadence dropped below 80 rpm for more than 10 s. The PPO was recorded as the highest workload achieved to the nearest 1 W (Barranco-Gil, *et al.*, 2020; Constantini, *et al.*, 2014; Nicolò, *et al.*, 2017).

The test was considered a true maximal effort if at least two of the following criteria were met:

- if HR failed to rise with increasing workload;
- if the rating of perceived exertion (RPE) at peak exercise was >17 on the 6–20 scale (Appendix D);
- if the participant indicated he / she was exhausted.

### 3.5.7 3-Min All-Out Cycling Test

Rider Critical Power (watts) was estimated from the 3-min all-out cycling test, and heart rate and RPE data were also recorded. This test was performed with the Cyclus2 ergometer in isokinetic test mode (i.e., fixed cadence). It has been shown that cadence affects the final 30 s of a 3-min all-out test, as well as CP estimated from protocols involving several constant-load exercise bouts (Vanhatalo *et al.*, 2008). Power output is a function of torque (resistance) and angular velocity (cadence), thus, by using a fixed cadence mode, a change in power output will be the result of a change in torque created by the muscles. Therefore, cadence was the set limit for the isokinetic test mode (Tsai, 2015; Wright *et al.*, 2017). The cadence set limit was individualized based on the participants' preferred cadence during the RI test. The average cadence maintained during the ramp test was rounded to the nearest tenth to determine the participant's cadence set limit for the 3-min all-out test (n=11 at 90 rpm, n=2 at 100 rpm). This means that participants were unable to obtain a higher cadence than the set limit and that resistance increased as a function of a higher pedaling rate.

The ergometer activated once the set cadence limit was reached, thus, participants were asked to slowly approach their predetermined cadence, after which they rapidly accelerated to a maximal sprint. Participants were instructed to cycle as fast as possible for the full duration of the test (3 min). The test was considered a true maximal effort if the rating of perceived exertion (RPE) at peak exercise was >17 on the 6–20 scale (Appendix D).

CP was calculated as the mean power output in the final 30 s of the 3-min all-out test and to the nearest 1 W (Black *et al.*, 2014; Vanhatalo *et al.*, 2007).

**Figure 3-2: Test set-up for the ramp incremental test.**

**(Photo taken by Rieta-Marie Brandt).**

### 3.5.8 20-Min Functional Threshold Power Test

Functional Threshold Power (FTP) was estimated from the 20-min time trial. Additionally, mean and maximal heart rate data and RPE were also recorded. The time trial mode of the Cyclus2 Ergometer was used to perform this test. Participants were able to adjust the torque during the test by changing the gear ratio using the handle-bar clip-ons (Inglis, *et al.*, 2020; Jeffries *et al.*, 2019; Karsten *et al.*, 2021). Participants were asked to maintain a constant, maximal power output for the full 20 min, whilst maintaining a cadence between 80-100 rpm.

FTP was calculated as 95% of the average power output over 20 min (Allan & Coggan, 2006; Miller *et al.*, 2014; Morgan *et al.*, 2019).

### 3.5.9 20 km and 40 km Time Trial

Performance times, heart rate and power variables and RPE were obtained from the 20 km (TT20) and 40 km (TT40) time trials. The ergometer was set on time trial mode. Participants were able to adjust the torque during the test by changing the gear ratio through handle-bar clip-ons. Participants were instructed to cycle the specific distance in the shortest time possible and were allowed their preferred pacing strategy whilst maintaining a cadence between 80-100 rpm.

## 3.6 STATISTICAL ANALYSIS

Statistical analysis was performed using the software IBM SPSS Statistics (version 28.0.0.0) and Microsoft Excel (version 16.63.1). Before data was analyzed, a Shapiro-Wilk test was performed to determine the distribution of data. The cycling test data all followed a normal distribution, except for CP and TT20 absolute power outputs. Descriptive statistics are presented as mean ± SD.

One-way repeated measures ANOVA with Bonferroni pairwise comparisons were used to analyze the difference between cycling test mean power outputs (PPO, FTP, CP, TT20 and TT40). Effect sizes (eta squared) between the power output measures were interpreted as 0.10 (small), 0.30 (moderate), 0.50 (large), 0.70 (very large), 0.90 (almost perfect) (Hopkins *et al.*, 2009).

The relationships between cycling power outputs (absolute and relative) and cycling time trial performance times (TT20 and TT40), were calculated using Pearson's product moment correlation coefficients (normally distributed data) and Spearman's rank correlation coefficients (non-normally distributed data). The correlations were interpreted as: r = 0.0 - 0.09 (trivial); r = 0.1 - 0.29 (small); r = 0.3 - 0.49 (moderate); r = 0.5 - 0.69 (large); r = 0.7 - 0.89 (very large); r = 0.9 - 0.99 (nearly perfect); r = 1 (perfect) (Bailey, 2021). Lin's concordance coefficient and the intraclass correlation coefficient (ICC) were calculated to evaluate the agreement between FTP and CP measures. ICC was interpreted as < 0.05 (poor); 0.5 - 0.75 (moderate); 0.75 - 0.9 (good); 0.9 (excellent reliability) (Koo & Li, 2016). Statistical significance was accepted at $p < 0.05$ for all tests.

# Chapter 4 RESULTS

## 4.1 PARTICIPANTS

### 4.1.1 Descriptive Characteristics

The data of 13 participants (8 men and 5 women) were included in the results (Table 4-1). The body fat percentage for the men and women fell within the ideal range according to the classification of Jackson & Pollock (1985) (healthy / acceptable / athletic). Cycling experience refers to the years of cycling training and racing. All participants had at least 3 years of cycling experience. Participants cycled for at least 6 hours on a weekly basis. The training hours indicated included cycling training, as well as running and/or swimming and/or strength training, with a minimum of 6 hours of *cycling* training per week.

The maximal exercise capacity responses (Table 4-2) were obtained from the ramp incremental cycling test. All efforts were considered a true maximal effort according to the ACSM criteria for a maximal test (Riebe *et al.*, 2018) (see section 3.5.1). All cyclists reached HRmax values equal to or higher than their age predicted HRmax (HRmax = 220 - age). The rating of perceived exertion (RPE) shows that participants experienced the ramp incremental test as *very, very hard* (Appendix D), which is indicative of maximal exertion. The $VO_{2max}$ (ml.kg.min$^{-1}$) and absolute PPO (W) results classify the study sample into the Performance Level (PL) 3 - 4 category, described as trained to well-trained (Decroix *et al.*, 2016 and De Pauw *et al.*, 2013).

**Table 4- 1: Participant Characteristics (n = 13)**

| Variables | mean ± SD | Min | Max |
|---|---|---|---|
| Age (y) | 33.1 ± 10.8 | 20.0 | 51.0 |
| Sex (M:F) | 8:5 | | |
| Body Fat % | 16.4 ± 7.0 | 8.8 | 26.2 |
| Weight (kg) | 71.4 ± 9.7 | 57.6 | 87.6 |
| Height (cm) | 175.0 ± 9.2 | 164.5 | 194.0 |
| Cycling Experience (yr) | 7.8 ± 4.2 | 3.0 | 18.0 |
| Weekly training (past 6 weeks) (hrs) | 10.6 ± 2.9 | 6.0 | 16.0 |

y: years; M:F: male:female; %: percentage; kg: kilograms; cm: centimeters; hrs: hours; SD: standard deviation; Min: minimum; Max: maximum.

**Table 4- 2: Maximal Exercise Capacity**

| Variables | mean ± SD | Min | Max |
|---|---|---|---|
| $VO_{2max}$ (mL·min$^{-1}$) | 3912.3 ± 867.7 | 2935.0 | 5402.0 |
| $VO_{2max}$ (mL·kg$^{-1}$·min$^{-1}$) | 54.5 ± 7.8 | 43.6 | 72.4 |
| PPO (W) | 337.7 ± 73.5 | 251.0 | 448.0 |
| PPO (W·kg$^{-1}$) | 4.7 ± 0.6 | 3.9 | 6.0 |
| $HR_{max}$ (bpm) | 187 ± 10.9 | 169 | 200 |
| % $HR_{max}$ (bpm) | 100 ± 0.1 | 100 | 101 |
| RPE | 19.1 ± 0.8 | 18 | 20 |

mL·min$^{-1}$: millilitres per minute; mL·kg$^{-1}$·min$^{-1}$: millilitres per kilogram per minute; W: watts; W·kg$^{-1}$: watts per kilogram; $HR_{max}$: maximum heart rate; % $HR_{max}$: percentage of $HR_{max}$; bpm: beats per minute; RPE: Rating of Perceived Exertion (6 - 20 scale).

### 4.1.2 Cycling Performance

The performance results presented in this section include the 40 km and 20 km time trials (Table 4-3), and the 20-minute FTP -and the 3-min all-out test (Table 4-4). All data sets were complete, except for the TT20 where one participant did not complete the trial due to illness.

**Table 4- 3: Time Trial Results**

| Variables | mean ± SD | Min | Max |
|---|---|---|---|
| TT40 (W) | 198.5 ± 55.0 | 137.0 | 296.0 |
| TT40 (W·kg$^{-1}$) | 2.7 ± 0.5 | 2.1 | 3.9 |
| TT40 (min) | 71.4 ± 7.8 | 60.5 | 86.0 |
| TT20 (W) | 217.8 ± 69.7 | 136.0 | 323.0 |
| TT20 (W·kg$^{-1}$) | 3.0 ± 0.7 | 2.1 | 4.4 |
| TT20 (min) | 34.3 ± 3.8 | 29.3 | 39.7 |

min: minutes; TT40: 40 km Time Trial; TT20: 20 km Time Trial

Power output is presented as *absolute* (W) and *relative* ($W \cdot kg^{-1}$) values. The average time of the participants for TT40 was 71.4 ± 7.8 min and 34.3 ± 3.8 min during TT20.

**Table 4- 4: Functional Threshold Results**

| Variables | mean ± SD | Min | Max |
|---|---|---|---|
| FTP (W) | 229.9 ± 63.3 | 156.0 | 335.0 |
| FTP ($W \cdot kg^{-1}$) | 3.2 ± 0.6 | 2.4 | 4.5 |
| CP (W) | 291.5 ± 78.2 | 211.0 | 441.0 |
| CP ($W \cdot kg^{-1}$) | 4.0 ± 0.7 | 3.3 | 5.3 |

FTP: Functional Threshold Power; CP: Critical Power

## 4.2 COMPARISON OF POWER OUTPUTS AMONG CYCLE PERFORMANCE TESTS

Figure 4-1 shows that the *absolute* PPO during the incremental ramp test was the highest for all the performance tests (337.69 ± 73.6 W). This power output was also significantly higher than the absolute values for TT40 (198 ± 55 W), TT20 (218 ± 70 W) and FTP (230 ± 63 W) ($p < 0.05$), but not for CP (291.46 ± 78.2 W, $p > 0.05$). Likewise, *relative* PPO (4.69 ± 0.56 $W \cdot kg^{-1}$) was significantly different from all other power values, TT40 (2.7 ± 0.5 $W \cdot kg^{-1}$), TT20 (3.0 ± 0.7 $W \cdot kg^{-1}$) and FTP (3.2 ± 0.6 $W \cdot kg^{-1}$) ($p < 0.001$), except CP (4.0 ± 0.7 $W \cdot kg^{-1}$) ($p > 0.05$). The *absolute* power output at CP and FTP were not statistically significantly different ($p > 0.05$). The *relative* power output at CP (4.0 ± 0.7 $W \cdot kg^{-1}$) was significantly different from the average power output during TT40 (2.7 ± 0.5 $W \cdot kg^{-1}$), TT20 (3.0 ± 0.7 $W \cdot kg^{-1}$) and FTP (3.2 ± 0.6 $W \cdot kg^{-1}$), ($p < 0.05$). The calculated effect sizes between *absolute* power outputs (ES = 0.38) and *relative* power outputs (ES = 0.61) were moderate to large.

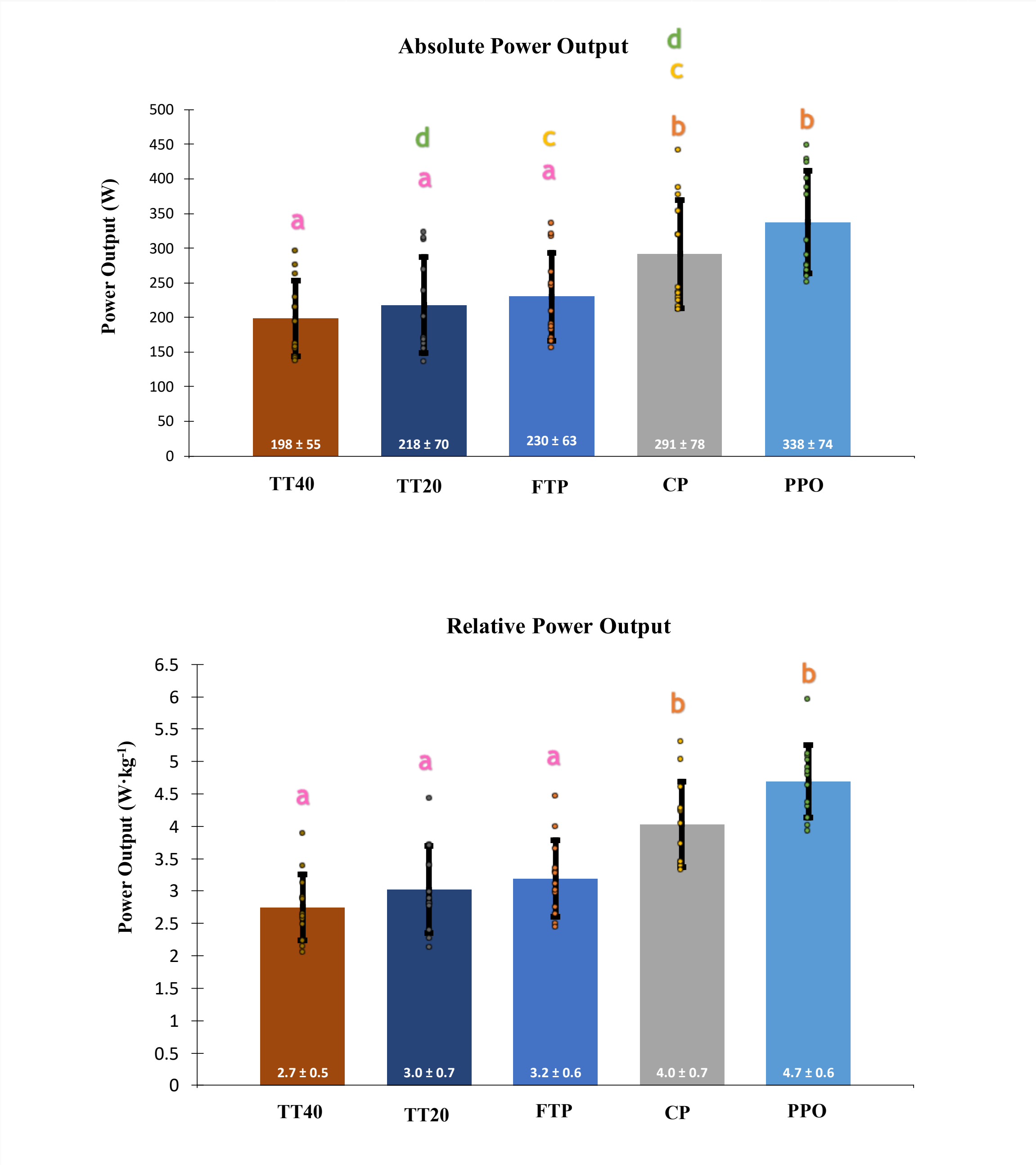
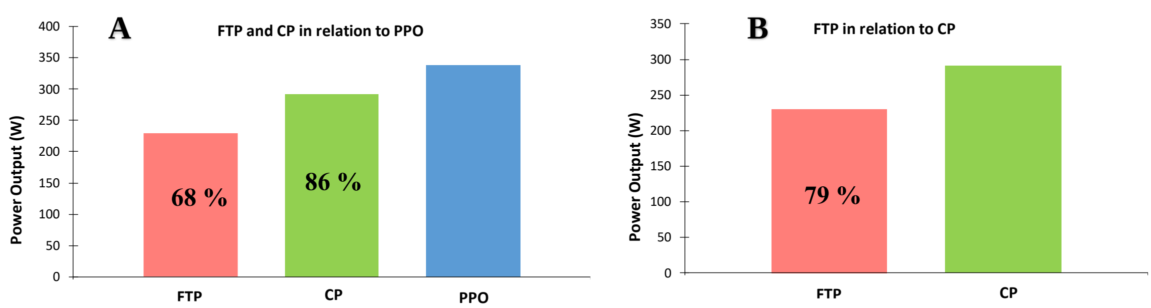
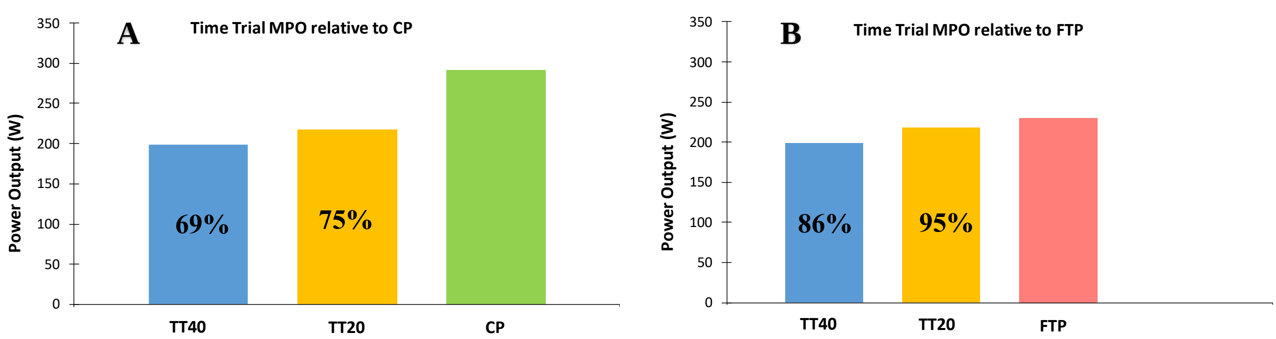



**Figure 4-1: Power Outputs from all Cycle Performance Tests**

TT40, TT20, the 20-min FTP test, the 3-min all-out test (CP) and PPO from the ramp incremental test. Bars that share a letter are not significantly different ($p > 0.05$). Bars that do not share a letter are significantly different ($p < 0.05$).

Figure 4-2 and 4-3 below shows the percentages at which the thresholds are located relative to each other, as well as the percentages of the MPO sustained during the time trials relative to FTP and CP. FTP and CP are located at 68 % and 85 % relative to rider PPO. respectively (Figure 4-2). FTP occurs at 79 % of power output at CP (Figure 4-2). Figure 4-3 shows that TT40 is located at a lower percentage (69 %) than TT20 (75 %) relative to FTP. Likewise, TT40 occurs at 86 % of rider CP compared to TT20 at 96 %.



## 4.3 THE RELATIONSHIP BETWEEN $VO_{2MAX}$, PPO AND THE FUNCTIONAL THRESHOLDS

Figure 4-4 represents the significant positive correlations that were observed between $VO_{2max}$ and both *absolute* and *relative* FTP values ($r = 0.58$ and $0.71$, $p < 0.05$). A significant correlation is present between $VO_{2max}$ and *relative* CP ($r = 0.63$, $p < 0.05$), but not between $VO_{2max}$ and *absolute* CP ($r = 0.40$, $p > 0.05$). $VO_{2max}$ presented significant negative correlations with both TT20 and TT40 ($r = -0.63$ and $-0.64$, respectively; $p < 0.05$).

Significant positive correlations between PPO and the functional thresholds: *absolute* measures (FTP: $r = 0.97$; $p < 0.001$; CP: $r = 0.93$, $p < 0.001$); and *relative* measures (FTP: $r = 0.89$; $p < 0.001$; CP: $r = 0.92$, $p < 0.001$), was observed (Fig 4-5, A-D). PPO presented a significant negative correlation with both time trial performance times: *absolute* measure (TT20: $r = -0.97$, $p < 0.001$; TT40: $r = -0.89$, $p < 0.001$); *relative* measure (TT20: $r = -0.83$, $p < 0.001$; TT40: $r = -0.82$, $p < 0.001$) (Fig 4-5, E - H).

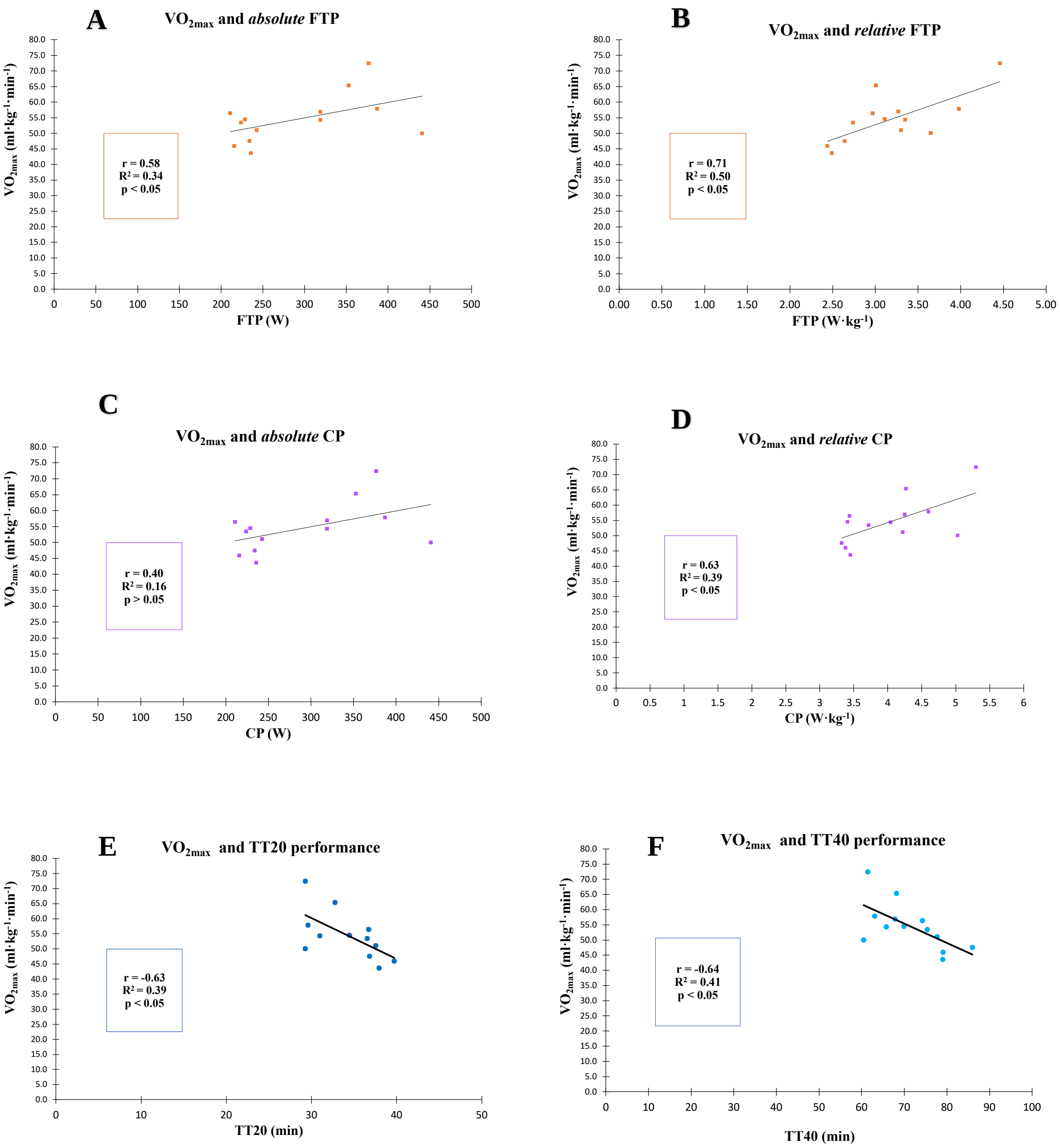



**Figure 4-2: Relationship of $VO_{2max}$ with Functional Threshold Power, Critical Power, TT20 and TT40**

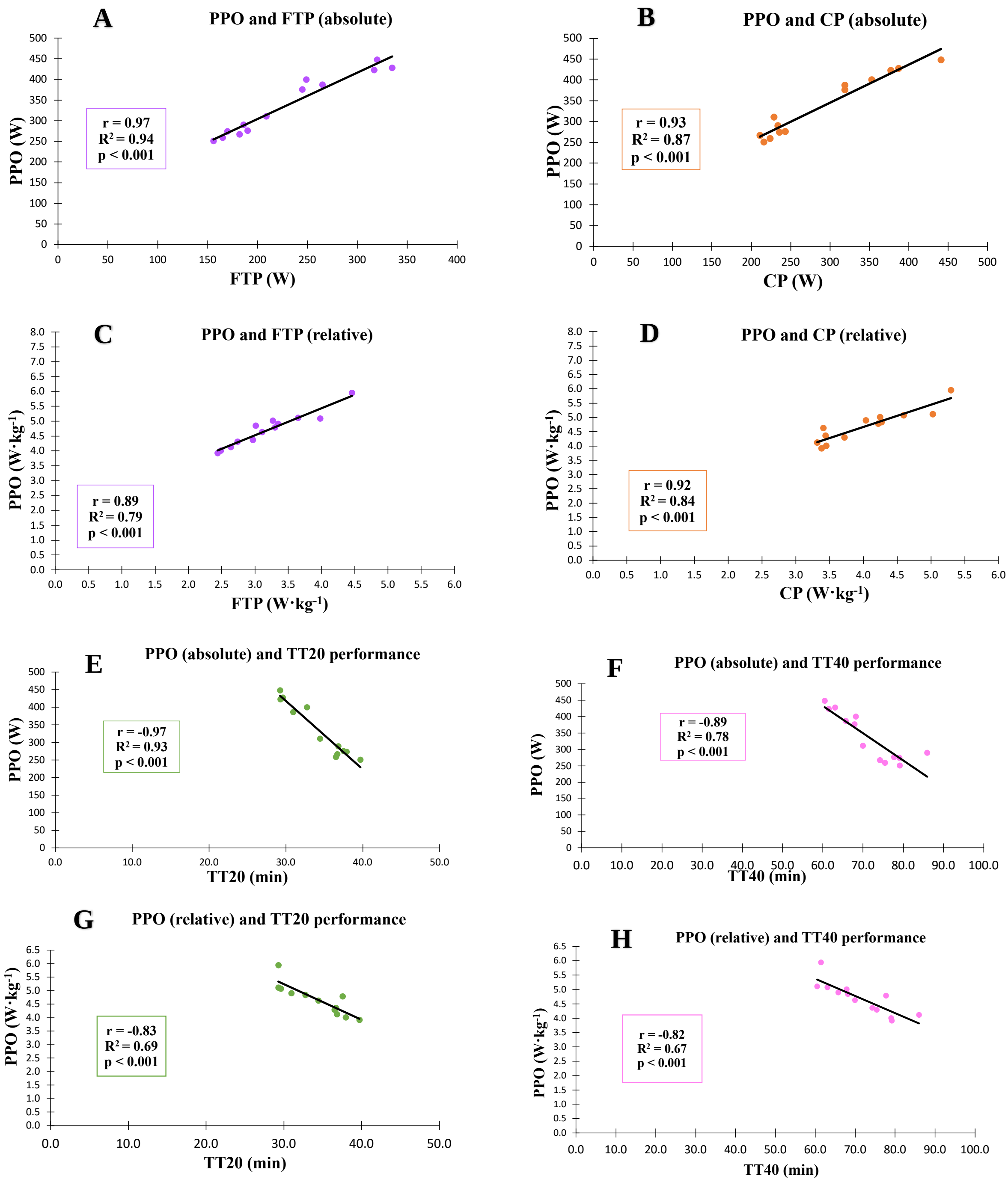



**Figure 4-3: Relationship of Peak Power Output and Functional Threshold Power, Critical Power and the Time Trials**

## 4.4 FTP AND CP RELATIONSHIP WITH CYCLING TIME TRIAL PERFORMANCE

Significant negative correlations were observed between both *absolute* and *relative* measures of FTP and CP and performance time of both TT20 and TT40 (r = -0.75 to - 0.97, $p < 0.001$) (Fig 4-6 and 4-7). A distinct grouping of data points was seen in the relationship between CP and time trial performances of TT20 and TT40 (Fig 4-6 and 4-7, C & D), and to a lesser extend between FTP and time trial performance (Fig 4-6 and 4-7, A & B). The upper cluster of data represents only male participants (n = 6). The difference between male and female group means for *absolute* FTP (265.8 ± 54.3 W *vs.* 172.6 ± 13.5 W) and CP (332.4 ± 73.6 W *vs.* 226.0 ± 13.4 W) was significant ($p < 0.05$).

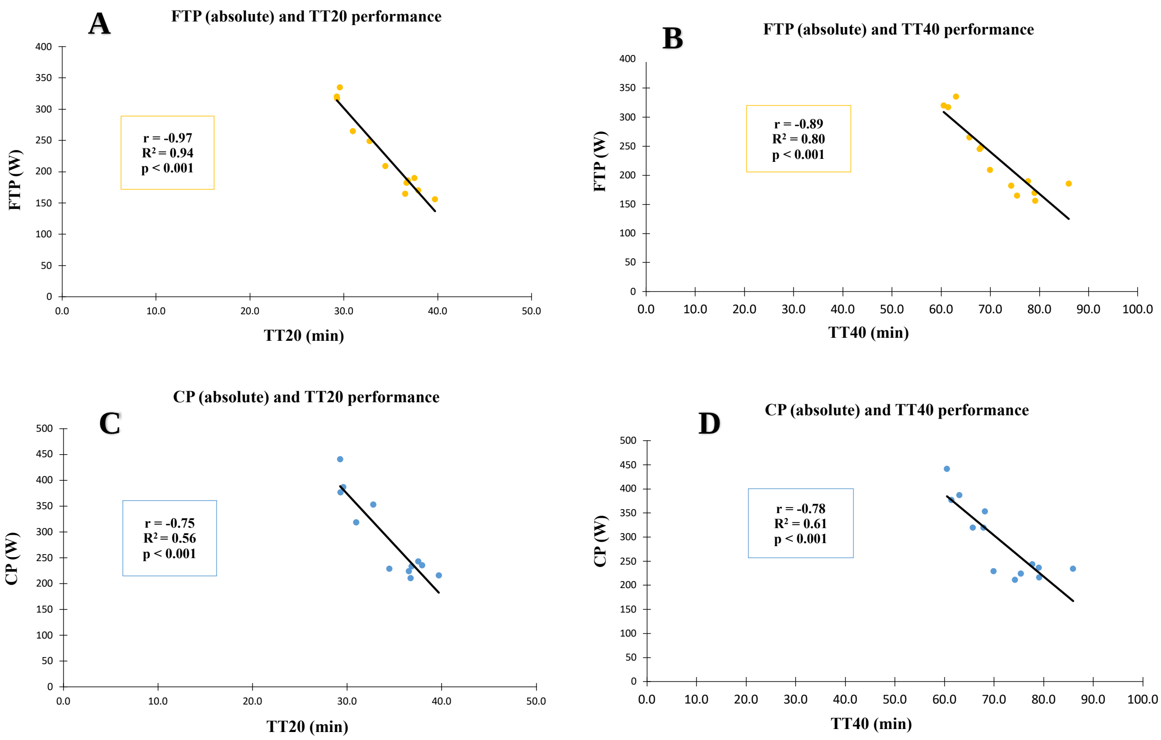



**Figure 4-4: Functional Threshold Relationship (*absolute* measures) with Time Trial Performance**

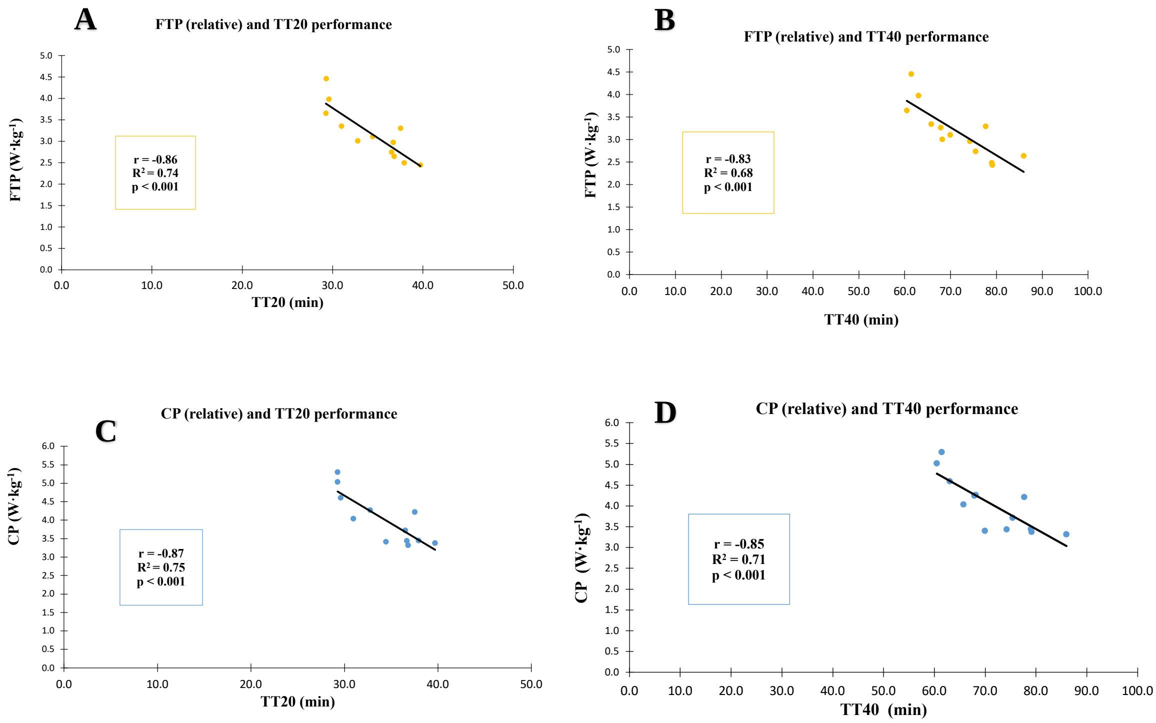



**Figure 4-5: Functional Threshold Relationship (*relative* measures) with Time Trial Performance**

No significant difference between *relative* FTP (3.4 ± 0.6 W·kg$^{-1}$ *vs.* 2.8 ± W·kg$^{-1}$, p = 0.05) and CP (4.3 ± 0.7 W·kg$^{-1}$ *vs.* 3.6 ± 0.3 W·kg$^{-1}$, p > 0.05) was observed between male and female cyclists. Significant positive correlations between *absolute* (r = 0.90, p < 0.001) and *relative* (0.96, p < 0.001) FTP and CP were observed (Fig 4-8). The intraclass correlation coefficient (ICC) for the *absolute* FTP and CP correlation (ICC = 0.68) (Fig 4-6, A) and *relative* correlation (ICC = 0.21) (Fig 4-8, B) was indicative of a moderate and poor reliability between these two parameters, respectively.

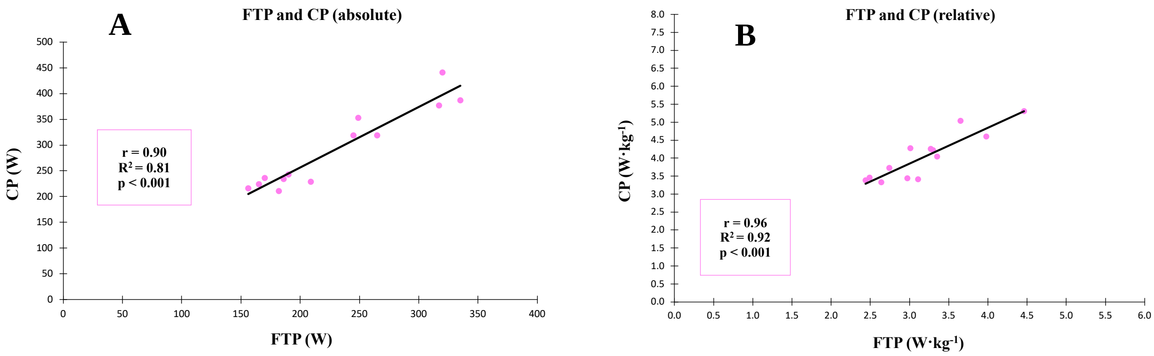



**Figure 4-6: Relationship of Functional Threshold Power and Critical Power**

*Absolute* measures (A) and *relative* measures (B).

## 4.5 PERFORMANCE TIME *VS*. MEAN POWER OUTPUT CORRELATIONS

Table 2-1 shows the results of the correlations between the thresholds and time trial performance time compared to time trial MPO. On average, for the TT20, stronger correlations exist between the **performance time** of the TT20 and the thresholds compared to the mean power output (MPO) sustained for the time trial. For the TT40, in contrast, stronger correlations exist when correlating MPO rather than performance times with FTP and CP.

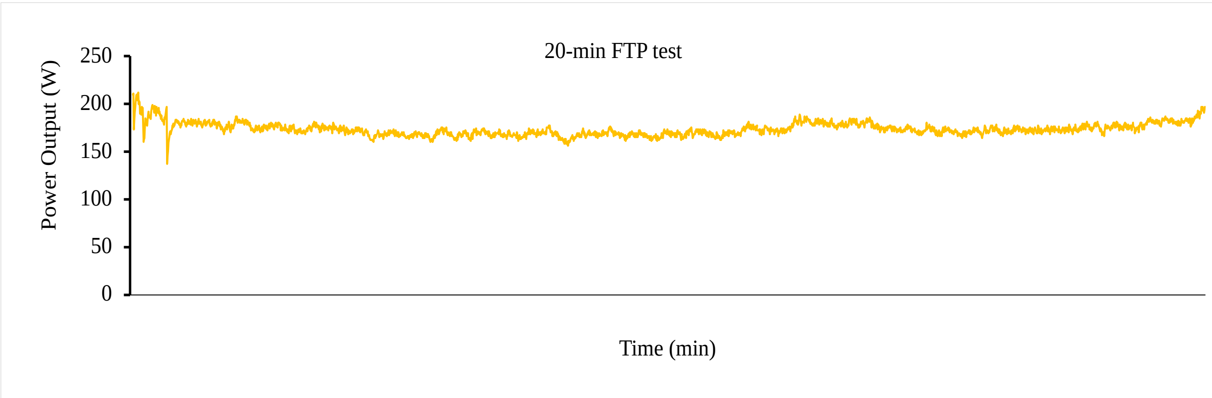
**Table 2-1: Correlation results of Time Trial MPO *vs*. Performance Times**

| TT20 | | |
|---|---|---|
| | MPO (*r values, p < 0.001*) | Performance Time (*r values, p < 0.001*) |
| CP (W) | **0.73** | **0.75** |
| CP (W·kg$^{-1}$) | **0.80** | **0.87** |
| FTP (W) | **0.90** | **0.97** |
| FTP (W·kg$^{-1}$) | **0.94** | **0.86** |
| PPO (W) | **0.88** | **0.97** |
| PPO (W·kg$^{-1}$) | **0.94** | **0.83** |

| TT40 | | |
|---|---|---|
| | MPO (r values, p < 0.001) | Performance Time (r values, p < 0.001) |
| CP (W) | **0.75** | **0.78** |
| CP (W·kg$^{-1}$) | **0.85** | **0.85** |
| FTP (W) | **0.97** | **0.89** |
| FTP (W·kg$^{-1}$) | **0.94** | **0.83** |
| PPO (W) | **0.97** | **0.89** |
| PPO (W·kg$^{-1}$) | **0.93** | **0.82** |

## 4.6 FTP AND CP PROFILES

These graphs show an example of the difference in power profiles of the 20-minute FTP test and the 3-min all-out test for CP determination. The 20-min FTP test entails a sustained, relatively constant power output for the full duration. The 3-min all-out entails an initial high power output which declines to a stabilized power output.



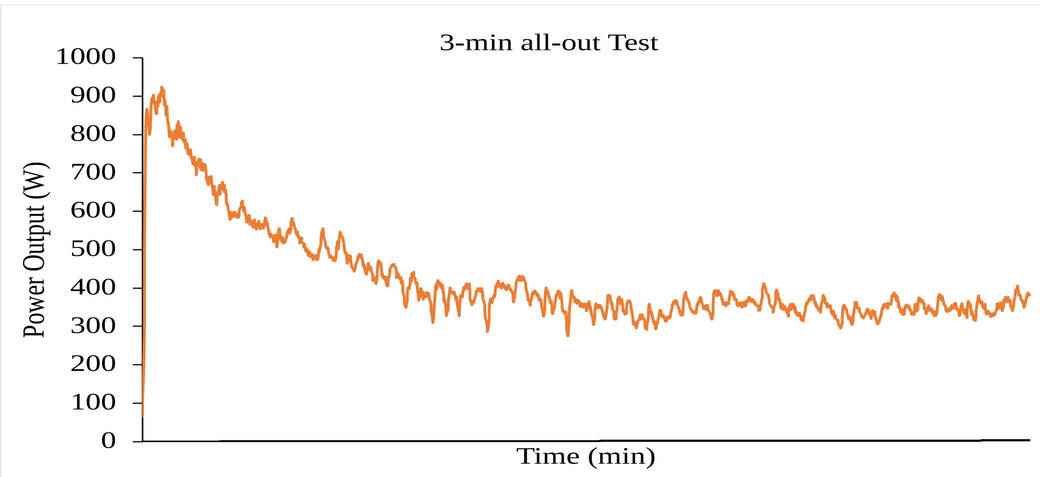




**Figure 4-7: Functional Threshold Power and Critical Power Test Power Profiles**

## 4.7 SUMMARY OF FINDINGS

### Table 4- 5: Summary of Correlations between all outcomes

| | Correlations, Coefficients of determination, p - values | | |
|---|---|---|---|
| | **r** | **variance** | **p** |
| $VO_{2max}$ - CP | 0.63 | 39% (0.39) | 0.022 |
| $VO_{2max}$ - FTP | 0.71 | 50% (0.50) | 0.007 |
| PPO ($W{\cdot}kg^{-1}$) - CP | 0.92 | 84% (0.84) | < 0.001 |
| PPO ($W{\cdot}kg^{-1}$) - FTP | 0.89 | 79% (0.79) | < 0.001 |
| FTP (W) - TT20 | -0.97 | 94% (0.94) | < 0.001 |
| FTP ($W{\cdot}kg^{-1}$) - TT20 | -0.86 | 74% (0.74) | < 0.001 |
| FTP (W) - TT40 | -0.89 | 80% (0.80) | < 0.001 |
| FTP ($W{\cdot}kg^{-1}$) - TT40 | -0.83 | 68% (0.68) | < 0.001 |
| CP (W) - TT20 | -0.75 | 56% (0.56) | < 0.001 |
| CP ($W{\cdot}kg^{-1}$) - TT20 | -0.87 | 75% (0.75) | < 0.001 |
| CP (W) - TT40 | -0.78 | 61% (0.61) | < 0.001 |
| CP ($W{\cdot}kg^{-1}$) - TT40 | -0.85 | 71% (0.71) | < 0.001 |

### Table 4- 6: Summary of Peak Power Output, Functional Threshold Power and Critical Power Power Outputs

**Power Output Comparison Summary**

**Absolute Measures**

| | | **PPO (W)** | **FTP (W)** | **CP (W)** |
|---|---|---|---|---|
| **PPO (W)** | 338 ± 74 | | $p < 0.05$ * | $p > 0.05$ |
| **FTP (W)** | 230 ± 63 | $p < 0.05$ * | | $p > 0.05$ |
| **CP (W)** | 291 ± 78 | $p > 0.05$ | $p > 0.05$ | |

**Relative Measures**

| | | **PPO ($W{\cdot}kg^{-1}$)** | **FTP ($W{\cdot}kg^{-1}$)** | **CP ($W{\cdot}kg^{-1}$)** |
|---|---|---|---|---|
| **PPO ($W{\cdot}kg^{-1}$)** | 4.7 ± 0.6 | | $p < 0.05$ * | $p > 0.05$ |
| **FTP ($W{\cdot}kg^{-1}$)** | 3.2 ± 0.6 | $p < 0.05$ * | | $p < 0.05$ * |
| **CP ($W{\cdot}kg^{-1}$)** | 4.0 ± 0.7 | $p > 0.05$ | $p < 0.05$ * | |

# Chapter 5 DISCUSSION

## 5.1 INTRODUCTION

The purpose of this study was to examine the associations between two functional thresholds, namely critical power (CP) and functional threshold power (FTP), and cycling performance in a laboratory setting. Both CP and FTP are power output measures related to a cyclist's endurance capacity, as was highlighted by the large correlations with $VO_{2max}$ (Fig 4-4). Both are promising and possibly more comprehensive parameters for the assessment of a cyclist's endurance performance ability. The main advantages of these thresholds are that they are objective measures of work done (i.e., power output) and not limited to singular metabolic parameters, such as lactate. Additionally, due to new technological innovations and widely available cycle power meters and trainers, functional thresholds can easily be measured by athletes and coaches, without requiring expensive laboratory equipment and scientific expertise.

Nevertheless, there are contrasting opinions surrounding the relationship of these two thresholds, which per definition, should represent physiological intensities in close approximation. The scope of this study was not to address these controversies, but rather provide some insight as to the potential practical application of these thresholds in cycling. The outcomes of this study would provide valuable information to coaches, athletes and practitioners, as it could guide their choice of functional threshold to assess and monitor race distance-specific readiness.

# 5.2 OVERVIEW OF FINDINGS

## 5.2.1 Primary Aims

- To examine the relationship of CP and FTP with known endurance performance markers, $VO_{2max}$ and PPO.

  ***Hypothesis 1**: CP and FTP will be more closely associated with PPO than $VO_{2max}$.*

  This hypothesis is **accepted**. CP and FTP significantly correlated with both $VO_{2max}$ and PPO, displaying a stronger relationship with PPO compared to $VO_{2max}$.

- To determine the correlation of CP with cycling performance over 20 km (TT20) and 40 km (TT40) cycling time trial.

  ***Hypothesis 2**: CP will be significantly correlated with both time trial distances.*

  This hypothesis is **accepted**. Both absolute (W) and relative ($W{\cdot}kg^{-1}$) measures of CP significantly correlated with both 20 km and 40 km cycling time trial performance times.

- To determine the correlation of FTP with cycling performance over a 20 km (TT20) and 40 km (TT40) cycling time trial.

  ***Hypothesis 3**: FTP will be significantly correlated with both time trial distances.*

  This hypothesis is **accepted**. Both absolute (W) and relative ($W{\cdot}kg^{-1}$) measures of FTP significantly correlated with both 20 km and 40 km cycling time trial performance times.

- To examine which threshold (CP or FTP) correlates strongest with the short (TT20) and long (TT40) time trial distance, respectively.

***Hypothesis 4****: CP will be more strongly correlated with TT20, whereas FTP will be more strongly correlated with TT40.*

This hypothesis is **partially accepted**. *Absolute* measures of FTP correlated more strongly with both TT distances compared with CP. There was no difference in the strength of the correlation between *relative* CP and FTP, and cycling time trial performances.

### 5.2.2 Secondary Aims

- To determine the difference between FTP, CP and PPO on the exercise intensity continuum.
  ***Hypothesis 5:*** *PPO will be significantly higher than both CP and FTP, and FTP and CP will not be significantly different.*

  This hypothesis is **partially accepted.** *Absolute* PPO was significantly higher than FTP, but not significantly higher than CP. *Absolute* CP was also not significantly higher than FTP. Likewise, *relative* PPO was significantly higher than FTP, but not significantly higher than CP. However, in contrast to the *absolute* measures, *relative* CP was significantly higher than FTP on the exercise intensity continuum.

## 5.3 SAMPLE CHARACTERISTICS

Thirteen (n = 13) individuals participated in this study. These individuals were trained to well-trained MTB riders, including men (n = 8) and women (n = 5), aged between 19 and 51 years. The decision to recruit MTB riders for this study, rested upon the knowledge regarding the mechanical and physiological differences between cycling specialists of uphill terrain (i.e., MTB riders) compared to cycling specialists of flat terrain (i.e., road cyclists). Physiological factors, such as blood lactate response during uphill riding, for example, differ between road and MTB specialists, where a greater increase in blood lactate during uphill exercise occur in road cyclists compared to MTB riders (Gandia Soriano *et al.*, 2020). Resultantly, flat terrain riders tend to have a greater rating of perceived exertion (RPE) when facing steep climbs compared to MTB specialists (Gandia Soriano *et al.*, 2020). Also, MTB riders have a greater capacity of neuromuscular activation needed for the steep uphills, which results in a greater variation in cadence (Ansley & Cangley, 2009; Arkesteijn *et al.*, 2013) compared to road cyclists. Thus, these riders' preferred cadences differ from the preferred cadence of road cyclists. Cadence affects the type of muscle motor unit recruitment during exercise, i.e., a lower cadence triggers the recruitment of more type II muscle fibers compared to the dominance of type I fibers during a higher cadence. This in turn, affects the cardio-respiratory and muscular response profiles of cyclists. For these reasons the recruitment of cyclists from the same specialization was justified.

The performance level of the participants were described according to the guidelines of Decroix *et al.* (2016) and De Pauw *et al.*, (2013). Accordingly, they were classified as trained to well-trained, based on their $VO_{2max}$ (ml.kg.min$^{-1}$), *absolute* PPO, weekly training hours and cycling experience (years). The sample performance level (PL) according to $VO_{2max}$ (ml.kg.min$^{-1}$) values were similar to the study sample of Black *et al.* (2014) and Morgan *et al.* (2019), compared to participants from (Sørensen *et al.* 2019) who were recreationally trained (PL 2). Likewise, the current sample classification based on PPO values were also similar to the participants in the studies of Black *et al.*, (2014) and Morgan *et al.*, (2019).

Previous studies comparing FTP and CP only included male participants. Even though sex comparison was not an aim of this study, the inclusion of women would allow the outcomes of this study to be extended to both male and female MTB riders. A significant difference between men and women was observed for *absolute* cycling performance measures, i.e., PPO (W), FTP (W), CP (W) and time trial performance times, TT20 and TT40. Coefficients of variation (Appendix F) showed that the inclusion of women did not affect time trial performances, but increased the inter-personal variation in *absolute* measures of PPO, FTP and CP. Thus, the calculated correlation coefficients (i.e., r-values) may have been inflated due to these significant differences. Nevertheless, the study outcomes agree with previous studies which only included men (Black *et al.*, 2014; Denham *et al.*, 2020; Miller *et al.*, 2014; Sørensen *et al.*, 2019), constituting that the current study outcomes deem viable.

Balmer *et al.* (2008) showed that 16.1 km cycling performance times of competitive male cyclists, ages 25 - 63 years, declined with age. This would lead to the concern that the current study's wide range of ages might have affected the outcomes. However, the data analysis (

Appendix F) showed that age and cycling performance for all cycling tests (i.e., power outputs and performance times) were not significantly related ($p > 0.05$).

## 5.4 CYCLING PERFORMANCE

The first cycling tests (the ramp incremental (RI) -and 3-min all-out test) for all participants in this study served as familiarization trials to allow participants to get used to the laboratory setting and the 3-min all-out test protocol. Based on the years of cycling experience and performance level of the participants, and a previous study that demonstrated that the mean performance times and power outputs of well-trained cyclists in a 20 km TT were not significantly different across three different trials (Thomas *et al.*, 2012), familiarization trials for TT20 and TT40 were deemed unnecessary.

To minimize the effect of nutrition and caffeine on the cyclist's performance during the tests, participants were asked to have their last meal at least 3 hours prior to their scheduled test, and avoid caffeine-containing drinks for 12 hours before testing. The researcher verified the cyclist's adherence to the pre-testing requirements by verbally asking the cyclists upon each laboratory visit. It is therefore assumed that all participants were honest in their confirmation of complying with the pre-testing requirements.

When cyclists are tested in a laboratory, one has the option of either blinding the rider from oral of visual feedback during the test or allowing feedback. Previous authors suggested that allowing cyclists to view their power output and heart rate data during cycling time trial tests, allows for optimal pacing strategies to be employed by the rider (Borg *et al.*, 2020; Brown & Bray, 2019). Additionally, researchers also argue that when participants are allowed to view their elapsed time and distance, it encourages individualized pacing (Miller *et al.*, 2014; Morgan *et al.*, 2019). It was therefore decided that participants in the current study would not be blinded to visual feedback during all the cycling tests. Verbal encouragement was provided during the RI and 3-min all-out tests to motivate cyclists to give an all-out effort. No verbal encouragement was given during the time trials, to avoid distracting them from their pacing strategy.

### 5.4.1 Limitations of Laboratory Cycling Performance Tests

Day-to-day intra-individual variability in cycling performance has been shown to be a prominent influencer of cycling performance in a laboratory setting (Sreedhara *et al.,* 2019). The only objective indication of their efforts was observed during the RI test, where it was confirmed that all the tests met the requirements for a maximal effort (Table 4-2). Therefore, it must be assumed that participant gave maximal efforts in all cases, however, there is no guarantee.

Due to technical difficulties with equipment, an alternative metabolic analyzer was used during the ramp incremental tests of three participants. However, both devices are from the same manufacturer and use the same software (Cosmed, Rome, Italy), therefore significant differences in the findings should not have occurred. Additionally, the $VO_{2max}$ values of these participants were not deemed outliers.

Three participants did not have a suitable bicycle to fit onto the Cyclus2 ergometer, therefore, they performed all their tests on a borrowed bike. The use of an unfamiliar bike could have influenced their cycling performance outcomes.

The study outcomes should be interpreted in light of these considerations and limitations.

## 5.5 RELATIONSHIP BETWEEN CP, FTP AND ENDURANCE PERFORMANCE MARKERS, $VO_{2MAX}$ AND PPO

The study findings show that $VO_{2max}$, PPO, FTP and CP were all significantly correlated with TT20 and TT40 performance times ($r = 0.63$ to $0.97$, $p < 0.05$). Furthermore, significant correlations between the functional thresholds (CP and FTP) and $VO_{2max}$ were observed ($r = 0.63 - 0.71$, $p < 0.05$), except for *absolute* CP ($r = 0.40$, $p > 0.05$). CP explained 39% of the variance in $VO_{2max}$ compared to FTP accounting for 50% of the variance in $VO_{2max}$. The relationships of PPO with time trial performance times (TT20 and TT40) were stronger than $VO_{2max}$ ($r = 0.89$ and $0.97$, $p < 0.001$ *vs.* $r = 0.63$ and $0.64$, $p < 0.05$), which suggests that PPO is more valuable to provide insights to cycling endurance performance capacity than $VO_{2max}$**.** $VO_{2max}$ and PPO are well known measures of cycling endurance performance capacity (Bassett & Howley, 2000; Burnley & Jones, 2007; Coyle, 1999; Jacobs *et al.*, 2011; Joyner & Coyle, 2008; Rønnestad *et al.*, 2019; van der Zwaard *et al.*, 2021). In fact, $VO_{2max}$ has been advocated as one of the most important performance indicators for endurance performance (De Pauw *et al.*, 2013), however, many researchers have shown that endurance performance success is not only attributed to $VO_{2max}$, but is also influenced by exercise economy and the percentage of $VO_{2max}$ (which is partly related to the lactate threshold) that can be sustained (Coyle, 1999; Coyle *et al.*, 1988; Joyner & Coyle, 2008; Lundby & Robach, 2015; Rønnestad *et al.*, 2019). Coyle *et al.*, (1988) showed that during a sub-maximal cycling test, individuals with the same $VO_{2max}$ values had different glycogen utilization and time to exhaustion results. Their performance differences were highly related to a combination of lactate production (i.e., % $VO_{2max}$ at lactate threshold) and muscle capillary density (lactic acid removal) ($r = 0.96$). A few other researchers (Coyle, 1999; Joyner & Coyle, 2008; Lundby & Robach, 2015), also reported other physiological factors apart from $VO_{2max}$ affecting endurance performance, such as a rider's lactate threshold and cycling efficiency. Thus, $VO_{2max}$ *is* valuable to give insight to a cyclists' aerobic potential, whereas PPO is *more* valuable to provide insights to cycling endurance performance capacity.

The current results also show that CP and FTP were both significantly correlated with PPO ($r = 0.89 - 0.97$, $p < 0.001$). These result outcomes suggest that the underlying physiology of CP and FTP includes but is not exclusively related to an athlete's maximal oxygen uptake ($VO_{2max}$), and that CP and FTP are valuable indicators of endurance performance capacity.

The current study outcomes agree with the notion that $VO_{2max}$ should not be singled out as the best measure of cycling endurance performance, but that FTP and CP should be considered as better measures. The latter finding, that CP is a better physiological parameter of endurance performance, is in agreement with previous findings (Jones *et al.*, 2019; Podlogar *et al.*, 2022). It can be argued that CP and FTP are more holistic endurance performance markers, as they account for different factors involved in high-intensity endurance exercise, e.g., the energy contribution from both aerobic and anaerobic sources, as well as lactate tolerance and measures of sustainable power outputs (Allen *et al.*, 2019; Jones *et al.*, 2019). $VO_{2max}$, in comparison, only accounts for the exercise capacity specific to a single metabolic parameter, namely oxygen uptake. In this study, $VO_{2max}$ explained a mere 39 - 41% of the variation in time trial performances compared to 85 - 97% variance explained by CP and FTP (Fig 4-4, E & F; 4-6 and 4-7). This is a clear indication that CP and FTP are better measures of cycling endurance performance than $VO_{2max}$ alone.

Considering the relationships of the two functional thresholds (CP and FTP) with PPO, it is evident that these power output measures are very closely associated. The nearly perfect correlations of the two functional thresholds (CP and FTP) with PPO (Fig 4-5, A-D) supports the argument above that CP and FTP significantly relates to a cyclist's maximal endurance exercise capacity. Past research stipulated that PPO is significantly correlated to cycling time trial performances ranging from 16 km to 40 km, signifying it as a key marker for cycling endurance success (Balmer *et al.*,2000; Bentley *et al.*, 2001; Hawley & Noakes, 1992; Lamberts & Davidowitz, 2014; McNaughton *et al.*, 2006). To my knowledge, the current study is the first to report the strong relationship between CP estimated from the 3-min all-out protocol and PPO (Fig 4-5, B & D). Therefore, it can be proposed that CP is a valid and valuable measure to assess a cyclist's maximal endurance capacity.

Likewise, a significant correlation was also observed between FTP and PPO in this study (Fig 4-5, A & C). Denham *et al.*, (2020) reported similar results ($r = 0.97$, $p < 0.001$) in a heterogenous cohort of cycle-trained and untrained individuals ($n = 40$). Due to the limited research that examined the relationship between FTP and known metabolic -and performance parameters, it has been argued that FTP lacks physiological clarity (Mackey & Horner, 2021; Sitko *et al.*, 2020).

It is quite concerning that very limited research exist exploring the physiological underpinnings of the FTP concept (Sitko *et al.*, 2022). Arguably, FTP cannot yet be regarded as a threshold, as no research has been done to establish the metabolic behavior associated with the threshold. Thus, FTP should rather be advocated as a performance measure rather than a threshold until research can confirm whether it is a physiological threshold in the first place. However, considering the current outcomes of the relationship between FTP and $VO_{2max}$ (Fig 4-4, A & B) and the close association of the threshold with cycling endurance performance (Fig 4-6 and 4-7, A & B), the current study provides preliminary evidence that FTP does offer convincing insights into a cyclist's cycling performance capacity.

## 5.6 RELATIONSHIP BETWEEN FTP AND TIME TRIAL CYCLING PERFORMANCE

Relative to the riders' FTP, the sustained power outputs were 86% for the TT40 and 95% for the TT20. The close proximity of the mean power output (MPO) sustained during the time trials to FTP suggests that FTP provides a good measure of time trial cycling performance capacity, with a stronger association with the shorter distance (20 km) (Fig 4-3 B). Furthermore, results revealed that FTP is significantly correlated with the performance times of both TT20 and TT40 (Fig 4-6 and 4-7, A & B). The strong negative relationships suggest that the higher a riders' FTP, the faster (i.e., shorter) their performance time over the set distance. Additionally, between the two time trial distances, a stronger relationship was observed between FTP and TT20 compared to TT40.

Previous research revealed similar findings. Miller *et al.* (2014) examined the relationship between FTP and the performance time of a 17.4 km MTB race in a group of competitive, male XCO-MTB riders (age = 35 ± 8 yr). They reported a significant relationship between FTP (3.32 ± 0.74 $W \cdot kg^{-1}$) and race performance time (69 ± 9 min) ($r = -0.86$, $R^2 = 0.74$, $p < 0.001$), which is the same as in the current study (Fig 4-7, A). Likewise, Morgan *et al.* (2019) showed that FTP (278 ± 42 W) significantly relates to the performance time (27 ± 2 min) of a 16.1 km road cycling time trial ($r = -0.87$, $R^2 = 0.76$, $p < 0.01$) in club-level male cyclists (ages 25 ± 7 yr). Importantly to note is that Miller *et al.*, (2014) reported the relative FTP ($W \cdot kg^{-1}$) in their study, while Morgan *et al.* (2019) reported the absolute FTP (W). Relative power ($W \cdot kg^{-1}$) is more critical in cycling performance on hilly terrain (especially uphills, such as in MTB racing ), where absolute power (W) is more important for flat terrain performance (Tan & Aziz, 2005).

The time trials in the current study were performed on a cycle ergometer and "flat" terrain, thus the absence of uphills in the time trials would explain why *absolute* FTP more strongly correlated with TT20 than *relative* FTP ($r = -0.97$ *vs.* $r = -0.86$, Fig 4-6 A *vs*. 4-7 A). It is speculated that if time trials were performed which more closely resembled MTB trails, or which included sections with steep climbs, the results may have favoured *relative* FTP rather than *absolute* FTP. Nevertheless, the current and previous studies confirm a clear connection between riders' FTP and their performance times over shorter distances / duration cycling efforts (i.e., 16 - 20 km; 27 - 34 min) , regardless of the type of terrain (i.e., MTB, road, "flat" terrain).

Other researchers also examined the relationship between FTP and performance time over a longer (47 km) MTB race in a group of moderately trained male cyclists (Sørensen *et al.*, 2019). A significant relationship between the riders' FTP ($W{\cdot}kg^{-1}$) and MTB race performance time was reported ($r = -0.74$, $R^2 = 0.55$, $p < 0.01$). This is a similar finding to the current study outcomes, which also revealed a significant relationship between FTP ($W{\cdot}kg^{-1}$) and TT40 ($r = -0.83$, $R^2 = 0.68$, $p < 0.001$).

The question is why a stronger correlation was achieved in the current study compared to Sørensen *et al.* (2019). Whereas Sørensen *et al.* (2019) concluded that 55% of the variance in performance times could be attributed to the riders' FTP, the association value of FTP in this study was 68%. It can be speculated that some (unreported) confounding factor(s) may have influenced the performance times of the MTB riders in the previous study, such as environmental conditions (e.g., heat, wind or rain), and technical skills associated with MTB riding. Participants from the current study performed the TT40 on an indoor cycle ergometer, thus, did not have these conditions to contend with. Furthermore, the race time in the previous study was 93 ± 6 min compared to the average time of 71 ± 8 min in the current study. As previously explained, it seems that FTP is stronger associated with cycling performance over shorter durations, i.e., < 93 minutes.

It was surprising to note that the riders from the study of Miller *et al.* (2014) cycled for 69 ± 9 min, which is very close to the current study's performance duration of 71 ± 8 min, even though the distances were very different (17.4 km outdoor MTB *vs.* 40 km on an indoor trainer). This would lead to the question why an exact same correlation coefficient ($r = -0.86$) for relative FTP ($W{\cdot}kg^{-1}$) was achieved from Miller *et al.*, (2014), which entailed a longer duration of cycling performance, compared to the TT20 from the current study, which lasted 34 ± 4 min. Once again, this is likely attributed to the terrain on which the time trials for the two studies were performed, i.e., involving uphills compared to a flat “road”. Confirming this line of reasoning, a much stronger relationship between *absolute* FTP and TT20, compared to *relative* FTP and TT20 was observed in the current study ($r = -0.97$ *vs.* $-0.86$).

The current study findings also showed that the correlation between FTP and TT20 is stronger than between FTP and TT40 (Fig 4-6 and 4-7, A *vs*. B). Thus, the association with FTP is more profound for shorter cycling performances compared to longer durations (e.g., 70 min *vs*. 90 min or 70 min *vs*. 30 min). Based on the definition of FTP, i.e., *the highest power output that a cyclist can maintain in a quasi-steady state for about 60 min* (Allen *et al.*, 2019), it was hypothesized that a stronger relationship between FTP and TT40 performance time (i.e., 71 ± 8 min) would be observed compared to the shorter TT20 (i.e., 34 ± 4 min). However, a *nearly perfect* correlation between absolute FTP with TT20, compared to a *very strong* correlation with TT40 (r = -0.97 *vs*. -0.86) was revealed. The most probable reason for this finding is attributed to the likely overestimation of FTP. The 95% correction factor that is applied to the mean power output in a 20-min TT to estimate FTP has previously been questioned (Inglis *et al.*, 2020; Lillo-Beviá *et al.*, 2019; MacInnis *et al.*, 2019). It was suggested that a stronger correction factor, such as 90% should be applied to avoid an overestimation of FTP (Lillo-Beviá *et al.*, 2019; MacInnis *et al.*, 2019), especially when using a less intense warm-up than the original warmup protocol (Allen *et al.*, 2019). A recent review study established that of the 15 existing studies on the 20-min FTP test, only 5 utilized the original prescribed warmup protocol (Mackey & Horner, 2021). Of the research studies mentioned in this chapter, only Miller *et al*. (2014) included the 5-min TT in their warm-up protocol, thus, their FTP estimate was unlikely overestimated. The use of a stronger correction factor (e.g., 90%) have not yet been validated by research, thus, it was decided to use the original correction factor of 95% to estimate FTP in the current study. Some authors suggested that the warmup undertaken before cycling time trials may affect result outcomes (Mackey & Horner, 2021). Others stipulated that a self-selected initial intensity prior to an exercise performance test (i.e., during the warmup), is considered an important component to performance outcomes (Stevens & Dascombe, 2015). It was therefore decided that the warmup performed prior to all cycling tests in the current study should be standardized, i.e., 10 minutes, allowing individuals freedom to choose their warmup intensity. The exclusion of the 5-min TT during the warm-up, together with the application of the 95% correction factor suggest that if FTP was overestimated, it will explain the stronger relationship with a cycling effort of higher intensity, i.e., 20 km TT, compared to a longer, 40 km TT.

Collectively, from the findings of Miller *et al.* (2014) and Sørensen *et al.* (2019), it can be concluded that *relative* FTP correlates stronger with cycling performance where a variation of inclination is present, i.e., where uphills are involved. In comparison, *absolute* FTP better associates with cycling performance on a more flat terrain, e.g., a road race / cycle ergometer time trial, as established by Morgan *et al.* (2019) and the current study. Ultimately, in concurrance with previous findings, the current study outcomes confirm that FTP is a valid measure of cycling endurance performance over a range of distances / durations.

## 5.7 RELATIONSHIP BETWEEN CP AND TIME TRIAL PERFORMANCE

To my knowledge, this is the first study to examine the relationship between the 3-min all-out test CP and a 20 km (TT20) -and 40 km (TT40) cycling time trials. Significant negative relationships were observed with both time trial performance times, indicating that a higher CP is associated with a faster performance time. Also, no difference was observed in the strength of these correlations, suggesting that CP has an equally strong association with both shorter (20 km) and longer (40 km) cycling bouts.

Only one similar study could be found where the researchers also determined CP from a 3-min all-out protocol. Black *et al.* (2014) reported that CP was significantly correlated with the performance time of a 16.1 km road cycling time trial ($r = -0.83$, $R^2 = 0.69$, $p < 0.01$), in a homogenous cohort of club-level, male cyclists (ages 34 ± 8 yr). This is in accordance with the similarly *very strong* relationship between *absolute* CP and TT20 performance time ($r = -0.75$, $R^2 = 0.56$, $p < 0.001$) in the current study. The slightly higher r-value of the previous study may be related to differences in the 3-min all-out protocol, as well as the shorter TT distance. The linear protocol (fixed resistance) used by Black *et al.* (2014) required participants to cycle at their preferred cadence against a pre-determined fixed resistance, which was established from a prior ramp incremental test (Vanhatalo *et al.*, 2007). The fixed resistance was set at an intensity halfway between the participant's gaseous exchange threshold (GET) and $VO_{2max}$. In the current study, the isokinetic protocol was used where the cadence was fixed so that the resistance increased when the rider exceeded the set cadence limit, i.e., trying to pedal faster (Tsai, 2015; Wright *et al.*, 2017). Nevertheless, the strong correlations observed in the two studies suggest that CP strongly associates with shorter TT performance (16.1 km and 20 km). The current study was also the first to report that CP is significantly associated with cycling time trial performance of a longer (40 km) TT. It was hypothesized that CP would associate more strongly with TT20 than with TT40, due to the greater intensity at which shorter time trials are performed. However, there was no difference in the correlation for the shorter (20 km) and the longer (40 km) time trial (Fig 4-6 and 4-7, C *vs*. D). The *absolute* and *relative* mean power output (MPO) for both TT20 and TT40 were not significantly different (Fig 4-1) and relative to the cyclists' CP, the sustained MPO were at 69 % and 75 % for the TT40 and TT20 respectively (Fig. 4-3 B). These results suggest that both these time trials fall in close proximity to each other, thus explains why CP correlates equally strong with both distances. Also, this finding could suggest that the underlying physiological mechanisms for both distances are accounted for by the CP threshold. Being beyond the scope of the current study, the possible physiological mechanisms underpinning this finding remain hypothetical. As we know, exercise within the heavy-intensity domain is associated with a steady metabolic milieu, compared to non-steady metabolism for intensities above CP, i.e., in the severe-I domain (Jones *et al.*, 2019; Vanhatalo *et al.*, 2011). Considering the percentage MPO relative to CP, both TT20 and TT40 are situated towards the upper end of the heavy-intensity domain and require an extended cycling bout of sustainable high-intensity exercise. Now, considering the 3 min all-out test used to estimate CP, the power decay shows that the initial cycling intensity is well above the CP threshold, i.e., within the severe-I domain. This intensity then exponentially declines to a plateau and a more sustainable intensity, which is indicative of an exercise intensity at which the aerobic energy system can achieve a steady state (Fig. 4-9). It is therefore possible that the strong correlations between CP and both TT20 and TT40 could suggest that common physiological mechanisms are involved during these time trials, involving both steady-state and non-steady state metabolic behaviors. TT20 occurs at a higher percentage relative to CP than TT40, which means that it is situated even closer to the severe-intensity domain. This would suggest that anaerobic mechanisms are more prominent during the shorter TT20 than during the TT40. It remains to be seen whether the relationship holds for longer distances than 40 km.

CP has been advocated as the "gold standard" marker for the transition between steady-state to non-steady-state exercise, suggesting that it represents the exercise intensity where a close interplay between aerobic and anaerobic metabolic processes occur (Jones *et al.* 2019; Pethick *et al.*, 2020). As previously discussed, rather than representing a distinct threshold, CP depicts an exercise intensity where a transition in metabolic behaviors occur (Pethick *et al.*, 2020), and is not limited by a single metabolic parameter (Jones *et al.*, 2019; Vanhatalo *et al.*, 2016). On the exercise intensity continuum, CP represents the transition between the heavy to severe-intensity domain (Fig 1-4). Thus, it could be inferred that TT performances over 20 to 40 km could be positioned within this "physiological transition zone", involving both steady-state and non-steady state metabolic behaviors. These intensity-associated behaviors would be highly individualized for each cyclist (Iannetta *et al.*, 2020) and would involve changes in muscle metabolic- and neuromuscular changes (Black, *et al.*, 2017), as well as parameters associated with aerobic and anaerobic metabolism (e.g., phosphocreatine concentration; blood pH;

inorganic phosphate; lactate and oxygen ($VO_2$) kinetics) (Jones *et al.*, 2008; Poole *et al.*, 2016; Vanhatalo *et al.*, 2016). Thus, the CP threshold captures the phenomenal interplay between the aerobic and anaerobic energy systems needed to match the physiological demands of cycling exercise involving bouts of higher intensities associated with shorter distances (e.g., 20 km), as well as lower intensities associated with longer distances (e.g., 40 km).

It was interesting to note that the relationship between *relative* CP ($W \cdot kg^{-1}$) and both TT20 and TT40 was stronger than for *absolute* CP (W) (Fig 4-7 *vs*. 4-6, C & D). Previous researchers have shown that anaerobic cycling performance is affected by body weight, specifically body composition, i.e., percentage body fat and percentage lean body mass (Maciejczyk *et al.*, 2015). The 3-min all-out test requires an initial reliance on primarily anaerobic energy sources, until the power output is reached where oxidative metabolic processes are more dominant, i.e., the last 30 s of the test (Burnley *et al.*, 2006; Vanhatalo *et al.*, 2007). This would explain why the inclusion of body weight into the equation enhances the association value of CP (Fig 4-7, C & D). Thus, the results of the current study suggest that *relative* CP values better associates with cycling endurance performance than *absolute* CP values.

## 5.8 THE RELATIONSHIP BETWEEN FTP AND CP

The current study is the first to reveal that FTP and CP estimated from the 3-min all-out test is significantly correlated ($r = 0.90 - 0.96$, $p < 0.001$, Fig 4-6). The nearly perfect correlation may suggest that these two thresholds share similar underlying physiological mechanisms. Future research should further explore the physiological mechanisms underpinning this significant relationship. It is quite concerning that very limited research exist exploring the physiological underpinnings of the FTP concept. Arguably, FTP cannot yet be regarded as a threshold, as no research has been done to establish the metabolic behaviors associated with the threshold. Thus, FTP should rather be advocated as a performance measure rather than a threshold until research can confirm whether it is a physiological threshold in the first place. From the current results (Fig. 4-2), FTP is located at 79% of rider CP. This would suggest that FTP is situated well within, towards the upper end, of the heavy-intensity domain. Also, FTP is located at 68 % relative to PPO, and CP at a much higher 86 %. The intraclass correlation coefficients (ICC) between FTP and CP for *absolute* (ICC = 0.68) and *relative* (ICC = 0.21) measures indicate moderate and poor levels of agreement, respectively. Therefore, it is suggested that these two thresholds should not be used interchangeably. Previous studies, reported similar findings between FTP and CP estimated from several constant load trials (Karsten *et al.*, 2021; McGrath *et al.*, 2021). These authors reported significantly strong correlations between FTP and CP ($r = 0.92$ to $0.97$, $p < 0.05$), however, also showed that large limits of agreement exists (-19 to 33 W and -40 to 40 W), suggesting that these two parameters should not be used interchangeably. Furthermore, Karsten *et al.*, (2021) and McGrath *et al.*, (2021) found that CP was significantly higher than FTP (256 ± 50 W *vs.* 249 ± 44 W and 282 ± 53 *vs*. 266 ± 55 W; $p < 0.05$). Morgan *et al.*, (2019), in contrast, found no significant difference between these two thresholds (275 ± 40 W *vs.* 278 ± 42 W; $p > 0.05$), however, also reported large limits of agreement (-36 to 30 W). Collectively, it can be accepted that these two thresholds are related, the large limits of agreement between FTP and CP suggest that they are not to be used interchangeably (Mackey & Horner, 2021).

Considering the power output percentages relative to FTP and CP that were sustained during the 20 km and 40 km time trials (Fig. 4-3), the results show that FTP is more closely associated with 20 km and 40 km time trial performance, as these intensities are in closer proximity to FTP compared to CP. These results suggest that FTP is more reflective of racing performance, in this case time trial performance, compared to CP. CP would arguably provide valuable information related to the physiological underpinnings of that performance, which should be explored by future research. Thus, it can be concluded that FTP is a stronger measure of cycling performance for both TT20 and TT40.

## 5.9 COMPARISON OF POWER OUTPUT AT FTP, CP AND $VO_{2MAX}$

From a visual observation, the power outputs associated with FTP, CP and PPO occur in a sequential order of increasing intensity: FTP < CP < PPO (Fig 4-1). The *absolute* PPO and power output at CP were not statistically significantly different. Power output at FTP and CP were also not significantly different while *absolute* PPO was significantly higher than FTP . Similarly, the *relative* power measures of CP and PPO revealed no significant difference, however, FTP was significantly lower than CP. Even though no significance was indicated, the difference between the *absolute* power outputs of PPO and CP (47 W) and CP and FTP (61 W), showed a moderate to large effect size (ES = 0.38). This suggests that these differences between the power outputs are meaningful. Likewise, the difference between the *relative* power outputs of PPO and CP (0.7 $W \cdot kg^{-1}$) are meaningful based on the large to very large effect size (ES = 0.61) indicated.

The power output at $VO_{2max}$ (i.e., PPO) gives an indication of a cyclist's *maximal* endurance capacity, whereas CP and FTP are related to an athlete's maximal *sustainable* endurance capacity. Although no past studies directly compared the power outputs of CP, FTP and PPO, researchers reported that PPO is situated at the higher end on the exercise intensity continuum in relation to CP and FTP (Denham *et al.*, 2020; Morgan *et al.*, 2019; Nicolò *et al.*, 2017; Vanhatalo *et al.*, 2007).

Considering the difference in power outputs at CP and FTP, research findings appear contradictory (Mackey & Horner, 2021). Per definition, both CP and FTP pertains to physiological processes associated with sustained endurance performance. Where CP is advocated as the "gold standard" measure of the highest exercise intensity where metabolic behaviors maintain a steady-state (Jones *et al.*, 2019; Podlogar *et al.*, 2022), FTP is regarded as the exercise intensity which is sustainable in a quasi-steady state without the onset of fatigue for approximately 60 minutes (Allen *et al.*, 2019). Thus, it would therefore be reasonable to expect that the power outputs of FTP and CP are in proximity on the exercise intensity continuum. However, based on the moderate to moderate to poor ICC from the current findings, in addition to the numerous reports of wide limits of agreements that exist between these two thresholds (Karsten *et al.*, 2021; Mackey & Horner, 2021; McGrath *et al.*, 2021; Morgan *et al.*, 2019), FTP and CP are unique thresholds and cannot be used interchangeably. The most apparent reason why existing research reports contradicting findings, is the inconsistencies in the methodology to establish these thresholds across the different studies (Poole *et al.*, 2021; Sitko *et al.*, 2020). Thus, more research is needed to establish the difference in power outputs of the two functional thresholds on the exercise intensity continuum.

## 5.10 STUDY LIMITATIONS

The protocol in this study to estimate FTP was similar to previous studies (Morgan *et al.*, 2019; Sørensen *et al.*, 2019), but different from the original protocol, which included a specific warmup (Allen *et al.*, 2019). It has been shown that the warm-up influences 20 min TT performance and FTP outcome (Borszcz *et al.*, 2019; Mackey & Horner, 2021; Tramontin *et al.*, 2022). Thus, in conjunction with findings that the 95% correction factor tends to overestimate FTP (Inglis *et al.*, 2020; Lillo-Beviá *et al.*, 2019), it is probable that the FTP in the current study was overestimated.

The significant difference observed between men and women for *absolute* cycling performance measures, i.e., PPO (W), FTP (W), CP (W) and time trial performance times, TT20 and TT40, may have resulted in inflated correlation coefficient values. Nevertheless, due to the agreement of the current findings with previous studies which only included men (Black *et al.*, 2014; Denham *et al.*, 2020; Miller *et al.*, 2014; Sørensen *et al.*, 2019), the current study outcomes deem viable.

An isokinetic (i.e., fixed cadence) 3-min all-out cycling test was used to estimate CP. Individualized and set cadence limits were based on the average cadence during the participants' ramp incremental test, rounded to the nearest ten. The cadence limit was set on 90 rpm for 11 participants, and 100 rpm for 2 participants, which was similar to the selected cadences of previous studies (Dekerle *et al.*, 2014; Wright *et al.*, 2017). However, as it is widely accepted that cadence affects cycling performance (Faria *et al.*, 2005) and due to the cadence limits not being the same for all participants, CP values and study outcomes may have been influenced.

Participants were permitted to change their pre-randomized testing schedule to suit their personal schedules, which reduced test randomization. This, however, was unlikely to pose a threat to the study outcomes, as the recovery time between cycling tests (at least 48 hours) were not changed.

The study only included trained to well-trained MTB riders. Thus, the study outcomes cannot be extrapolated to recreational and elite road cyclists.

The sample size was small for such a heterogeneous sample. This study can be regarded as an exploratory study paving the way for more research in this area of functional thresholds.

# Chapter 6 Conclusion

## 6.1 OVERVIEW OF FINDINGS

The findings of the current study permit the following conclusions:

**Hypothesis 1** is **accepted**. CP and FTP significantly correlated with both $VO_{2max}$ and PPO, with a stronger relationship observed with PPO.

**Hypothesis 2** is **accepted**. Both absolute (W) and relative ($W \cdot kg^{-1}$) measures of CP significantly correlated with both 20 km and 40 km cycling time trial performance times.

**Hypothesis 3** is **accepted**. Both absolute (W) and relative ($W \cdot kg^{-1}$) measures of FTP significantly correlated with both 20 km and 40 km cycling time trial performance times.

**Hypothesis 4** is **partially accepted**. *Absolute* measures of FTP more strongly correlated with both TT20 and TT40 than CP. There was no difference in the correlation strength between *relative* CP and FTP and cycling time trial performance times of TT20 and TT40.

**Hypothesis 5** is **partially accepted.** *Absolute* PPO was significantly higher than FTP, but not significantly higher than CP. *Absolute* CP was also not significantly higher than FTP. Likewise, *relative* PPO was significantly higher than FTP, but also not significantly higher than CP. However, different from *absolute* measures, *relative* CP was significantly higher than FTP on the exercise intensity continuum.

The conclusion of this study is that both functional thresholds, CP and FTP (*absolute* and *relative* measures), are valid and valuable measures of cycling endurance performance for 20 km and 40 km distances. Between the two thresholds, *absolute* FTP shows to be the best associated with cycling time trial performance for both 20 km and 40 km distances.

## 6.2 PRACTICAL IMPLICATION

Today, the use of mobile power meters and cycle ergometers as a training tool are widespread among cyclists of all abilities and it allows for convenient and direct measures of functional thresholds. Being objective measures of work done against time, functional thresholds offer a true representation of actual performances (e.g., races; events; time trials) and are not limited to singular metabolic parameters. Furthermore, functional thresholds offer an advantage in that they do not require expensive laboratory equipment and expertise on the interpretation of metabolic measurements; thus, they are more accessible to coaches and athletes.

The outcomes of the present study suggest that both FTP and CP are valid and valuable measures associated with cycling endurance performance, and offers promise of being comprehensive in nature in describing an athlete's cycling endurance performance capabilities across different distances (20 km and 40 km). Coaches, athletes, and practitioners are better informed as to which functional threshold (CP or FTP) to use as an objective measure to evaluate and monitor training progress for specific race-distance goals.

## 6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

Being the first study to examine the relationship between CP from the 3-min all-out (isokinetic) protocol with cycling performance of different durations, more research is needed to validate these findings. Additionally, validation of the current results in the field is needed, i.e., does CP determined in the laboratory predict time trial performance in the field.

Future studies could examine the relationship between CP and FTP with shorter and longer distances (e.g., 5 km and 80 km) to assess the effect of cycling distance on the association value of the functional thresholds.

CP, promoted as the "gold standard" threshold demarcating sustainable from non-sustainable exercise, suggests that CP could be an essential parameter in training zone determination. Thus, future studies could explore the use of CP determined by the 3-min all-out protocol and the establishment of training zones.

Future research should evaluate the relationship between CP determined by the 3-min all-out protocol and cycling performance associated with high normalized power (e.g., a mountain bike race) compared to sustained efforts (e.g., a road race / flat TT).

Future research should evaluate the physiological responses above & below FTP (e.g., oxygen and lactate kinetics) to provide clarity into the physiological mechanisms of the FTP concept and to actually determine whether FTP can be regarded as a threshold.

FTP is popularly used to prescribe training zones, however, due to inconsistencies in FTP determination methods, the under -or overestimation of FTP is a concern. This poses the risk to athletes to over -or undertrain, which would negatively impact their performance. Thus, future studies should establish protocols to limit the risk of over -or underestimating FTP.

Research on FTP, CP and cycling performance in women cyclists is scarce. Thus, future studies examining these functional thresholds should include the female cycling population. As we know that meaningful physiological and performance differences exist between men and women (Hunter, 2016; Joyner & Coyle, 2008; Phillips & Hopkins, 2020), it would be of great value to conduct sex comparisons in the relationship of the respective thresholds with cycling performance of different distances.

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# Appendices

## Appendix A: Recruitment Flyer

Appendix B: ACSM Medical Screening Questionnaire

# 2020 PAR-Q+

## The Physical Activity Readiness Questionnaire for Everyone

The health benefits of regular physical activity are clear; more people should engage in physical activity every day of the week. Participating in physical activity is very safe for MOST people. This questionnaire will tell you whether it is necessary for you to seek further advice from your doctor OR a qualified exercise professional before becoming more physically active.

## GENERAL HEALTH QUESTIONS

| **Please read the 7 questions below carefully and answer each one honestly: check YES or NO.** | **YES** | **NO** |
|---|---|---|
| 1) Has your doctor ever said that you have a heart condition ☐ **OR** high blood pressure ☐? | ☐ | ☐ |
| 2) Do you feel pain in your chest at rest, during your daily activities of living, **OR** when you do physical activity? | ☐ | ☐ |
| 3) Do you lose balance because of dizziness **OR** have you lost consciousness in the last 12 months? Please answer **NO** if your dizziness was associated with over-breathing (including during vigorous exercise). | ☐ | ☐ |
| 4) Have you ever been diagnosed with another chronic medical condition (other than heart disease or high blood pressure)? **PLEASE LIST CONDITION(S) HERE:** ______ | ☐ | ☐ |
| 5) Are you currently taking prescribed medications for a chronic medical condition? **PLEASE LIST CONDITION(S) AND MEDICATIONS HERE:** ______ | ☐ | ☐ |
| 6) Do you currently have (or have had within the past 12 months) a bone, joint, or soft tissue (muscle, ligament, or tendon) problem that could be made worse by becoming more physically active? Please answer **NO** if you had a problem in the past, but it **does not limit your current ability** to be physically active. **PLEASE LIST CONDITION(S) HERE:** ______ | ☐ | ☐ |
| 7) Has your doctor ever said that you should only do medically supervised physical activity? | ☐ | ☐ |

**If you answered NO to all of the questions above, you are cleared for physical activity.**
**Please sign the PARTICIPANT DECLARATION. You do not need to complete Pages 2 and 3.**

- Start becoming much more physically active – start slowly and build up gradually.
- Follow Global Physical Activity Guidelines for your age (https://apps.who.int/iris/handle/10665/44399).
- You may take part in a health and fitness appraisal.
- If you are over the age of 45 yr and NOT accustomed to regular vigorous to maximal effort exercise, consult a qualified exercise professional before engaging in this intensity of exercise.
- If you have any further questions, contact a qualified exercise professional.

**PARTICIPANT DECLARATION**
If you are less than the legal age required for consent or require the assent of a care provider, your parent, guardian or care provider must also sign this form.

I, the undersigned, have read, understood to my full satisfaction and completed this questionnaire. I acknowledge that this physical activity clearance is valid for a maximum of 12 months from the date it is completed and becomes invalid if my condition changes. I also acknowledge that the community/fitness center may retain a copy of this form for its records. In these instances, it will maintain the confidentiality of the same, complying with applicable law.

NAME ______________________ DATE ______________

SIGNATURE ______________________ WITNESS ______________

SIGNATURE OF PARENT/GUARDIAN/CARE PROVIDER ______________________

**If you answered YES to one or more of the questions above, COMPLETE PAGES 2 AND 3.**

**Delay becoming more active if:**

- You have a temporary illness such as a cold or fever; it is best to wait until you feel better.
- You are pregnant - talk to your health care practitioner, your physician, a qualified exercise professional, and/or complete the ePARmed-X+ at www.eparmedx.com before becoming more physically active.
- Your health changes - answer the questions on Pages 2 and 3 of this document and/or talk to your doctor or a qualified exercise professional before continuing with any physical activity program.

Appendix C: Participant Information and Consent Forms

PARTICIPANT INFORMATION

| **TITLE OF RESEARCH PROJECT:** | |
|---|---|
| Functional Thresholds as predictors of 20- and 40km Cycling Performance. | |
| **DETAILS OF PRINCIPAL INVESTIGATOR (PI):** | |
| **Ms Rieta-Marie Brandt** | **Ethics reference number:** **23701** |
| **Full postal address:** Department Sport Science, Stellenbosch University, Private Bag X1, Matieland, Stellenbosch, 7601 | **PI Contact number:** 0725772020 |

We would like to invite you to take part in a research project. Please take some time to read the information presented here, which will explain the details of this project. Please ask the study staff any questions about any part of this project that you do not fully understand. It is very important that you are completely satisfied that you clearly understand what this research entails and how you could be involved. Also, your participation is **entirely voluntary,** and you are free to decline to participate. In other words, you may choose to take part, or you may choose not to take part. Nothing bad will come of it if you say no: it will not affect you negatively in any way whatsoever. Refusal to participate will involve no penalty or loss of benefits or reduction in the level of care to which you are otherwise entitled to. You are also free to withdraw from the study at any point, even if you do agree to take part initially.

This study has been approved by the **Health Research Ethics Committee at Stellenbosch University.** The study will be conducted according to the ethical guidelines and principles of the international Declaration of Helsinki, the South African Guidelines for Good Clinical Practice (2006), the Medical Research Council (MRC) Ethical Guidelines for Research (2002), and the Department of Health Ethics in Health Research: Principles, Processes and Studies (2015).

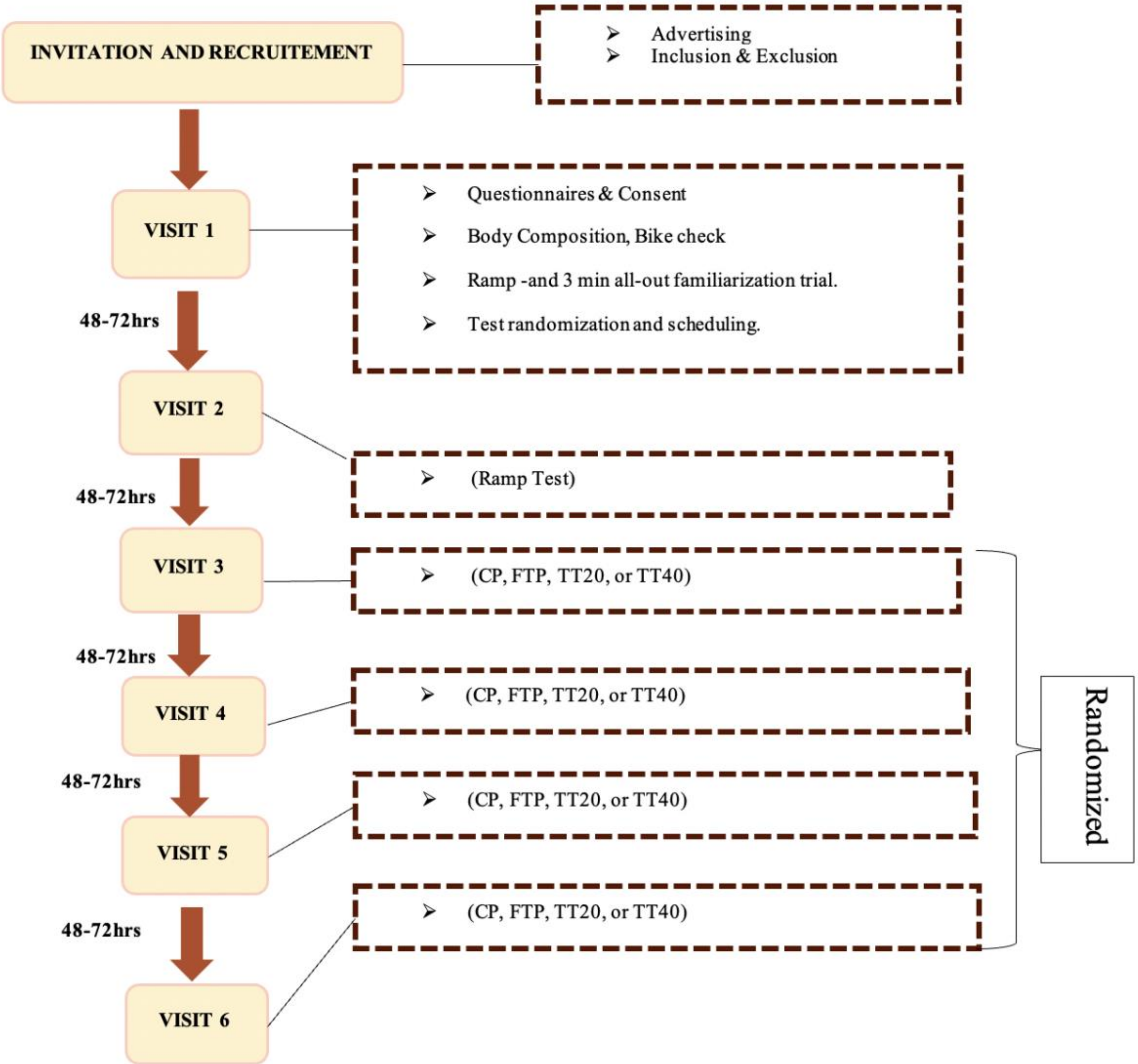
*What is this research study all about?*

The purpose of this study is to evaluate functional thresholds, Critical Power (CP) and Functional Threshold Power (FTP) as predictors of cycling performance for a shorter 20 km (TT20) -and longer 40 km time trial (TT40), respectively. CP will be determined by a 3-minute all-out cycling test, and FTP by a 20 minute maximal effort time trial. 20 km and 40 km cycling time trials will also be performed, as well as a ramp incremental test will be performed to determine peak power output (PPO).

If you agree to take part in the study and the screening procedure indicate that you are eligible, you will be invited to attend the first procedures in the laboratory, which will last at least an hour. Your height, weight and body metrics will be measured. Additionally, upon your first visit, a bike fit will be conducted, ensuring that you are comfortably positioned the same on the bike for all subsequent tests. Thereafter, you will be performing a 3-minute all-out tests, followed by a 30 minute rest, and then a ramp incremental test. Upon your next visit, you will once again perform a ramp incremental test. Visits 3-6 will occur in a randomized fashion for all participants, consisting of a 3-minute all-out test, a 20 min time trial, a 20 km time trial (TT20) and a 40 km time trial (TT40). Your testing schedule will be determined during your first visit to the laboratory (see figure below).

For all tests, you will be fitted with a chest heart rate monitor. For the TT20 and TT40, you will have the option to drink water *ad libitum*. You will, however, not be allowed to consume any carbohydrate / nutrition during the tests.

The study will be conducted in the Sport Physiology Laboratory in the Department of Sport Science. We will invite 40 road cyclists (men and women) to participate in the study and recruitment will continue until we achieve this number. The testing will take 2 – 3 weeks, as each test must be separated by at least 48 hours to ensure sufficient recovery. Important to note, it that this testing period might interfere with your training, as you will not be allowed to do hard training the day before your tests. You will be expected to give a maximal effort for the duration of all tests. Additionally, your own personal bike and cycling kit should accompany you the laboratory. At the end of the testing period, you will be provided with a report containing your test results.




*Why do we invite you to participate?*

You are invited to take part in this study because you have indicated your interest in the research project by responding voluntarily to the invitation and you meet the inclusion criteria for the study. The inclusion criteria stipulate that you are a trained to well-trained road cyclist, actively participating in deliberate cycling exercise at least 8 hours per week and aged between 19 and 49 years.

*What will your responsibilities be?*

We ask that you complete all questionnaires honestly and that you follow the instructions of the researchers during all phases of the testing procedures. You will also be asked to give your best efforts during the cycle ergometer tests. In case of not adhering to the pre-testing procedures (see the list below), we ask that you please inform the researcher.

Important pre-testing procedures:

1. eat your last meal / snack at least 3 hours before your testing;
2. avoid caffeine-containing drinks and alcohol ingestion at least 12 hours before testing;
3. avoid vigorous activities – RPE above 12 on the Borg scale - or any unaccustomed exercise at least 24 hours before testing;
4. stay well hydrated prior to testing.

*Will you benefit from taking part in this research?*

No participant will be compensated for their participation in this study. You will receive a full written report of your individual test results from the researcher. Additionally, participants will be receiving a summary of the main findings of the study once the study has been completed. This study could contribute to the specificity of training, by providing insight to coaches and training practitioners as to which functional threshold is best correlated with longer (i.e., 40 km) *vs.* shorter (i.e., 20 km) cycling performance. Ultimately, this would guide coaches, athletes, and practitioners in using the more appropriate cycling test to evaluate, monitor and predict specific race readiness.

*Are there any risks involved in your taking part in this research?*

There will be no serious risks involved in the study; nonetheless, you may experience dizziness, physical discomfort, muscle fatigue and in rare instances, fainting, during the cycling tests. In the case that you experience any of these symptoms the exercise test will be stopped immediately, and the researchers will take the necessary steps to make you comfortable. Should any serious emergency arise, you will be stabilized and transported to the emergency room of Stellenbosch Medi-Clinic.

*Even though it is unlikely, what will happen if you get injured somehow because you took part in this research study?*

Stellenbosch University will provide comprehensive no-fault insurance and will pay for any medical costs that came about because participants took part in the research, as a result of the exercise testing in the laboratory. The participant will not need to prove that the researchers were at fault.

*Are there any costs involved?*

You will not have to pay for anything. You are, however, responsible for your own transport to the laboratory for all your tests.

*Is there anything else that you should know or do?*

If you have any questions or concerns about the study or procedures, please feel free to contact Rieta-Marie Brandt [0725772020; 18973078@sun.ac.za] and/or the supervisor Prof Elmarie Terblanche [082 7076501; et2@sun.ac.za].

You may phone the Health Research Ethics Committee at 021 938 9677/9819 if there still is something that the researchers have not explained to you, or if you have a complaint.

You will receive a copy of this information and consent form for you to keep safe.

*CONSENT FORM - English*

*Declaration by participant*

By signing below, I …………………………………..………… agree to take part in a research study entitled *“Functional thresholds as predictors of 20- and 40 km cycling performance”*.

I declare that:

- I have read this information and consent form, or it was read to me, and it is written in a language in which I am fluent and with which I am comfortable.
- I have had a chance to ask questions and I am satisfied that all my questions have been answered.
- I understand that taking part in this study is **voluntary,** and I have not been pressurised to take part.
- I may choose to leave the study at any time and nothing bad will come of it – I will not be penalised or prejudiced in any way.
- I may be asked to leave the study before it has finished, if the study doctor or researcher feels it is in my best interests, or if I do not follow the study plan that we have agreed on.

Signed at (*place*) ......................…........…………….. on (*date*) …………...……….. 2021.

..................................................................... ............................................................

**Signature of participant** **Signature of witness**

*Declaration by investigator*

I *(name)* ……………………………………………..……… declare that:

- I explained the information in this document in a simple and clear manner to …………………………………..
- I encouraged him/her to ask questions and took enough time to answer them.
- I am satisfied that he/she completely understands all aspects of the research, as discussed above.
- I did/did not use an interpreter. (*If an interpreter is used then the interpreter must sign the declaration beloW·)*

Signed at (*place*) ......................…........…………….. on (*date*) …………...……….. 2021.

...................................................................... ..............................................................

**Signature of investigator** **Signature of witness**

*Permission to use all anonymous data to be shared with journals:*

We would like to publish results of this study in relevant journals. This will require us to share your anonymous data with the relevant journal before they publish the results. Therefore, we would like to obtain your permission to share your anonymous data with journals.

**Please indicate your option of permission:**

I hereby **give permission** to the sharing of my anonymous data with journals for publication purposes.

☐ Signature____________

OR

I hereby **deny permission** to the sharing of my anonymous data with journals for publication purposes.

☐ Signature____________

*Permission for sharing samples and/or information with other investigators:*

Data collected from this study, might be requested for future studies. Therefore, we would like to store the results obtained during this study and share the data with future investigators. Other investigators from all over the world can request to use our results in future research. To protect your privacy, your name will be replaced with a unique numerical code. All your data will be saved as your code; thus, your information will remain anonymous. We will do our best to keep the code private. Therefore, we would like to ask for your permission to share your data and information with other investigators.

Please indicate your option of permission:

I hereby **give permission** to the sharing of my anonymous data with other investigators.

☐ Signature____________

OR

I hereby **deny permission** to the sharing of my anonymous data with other investigators.

☐ Signature____________

## *VRYWARINGSVORMS - Afrikaans*

### *Verklaring van deelnemer*

Deur die onderstaande te teken, stem ek …………………………………..………… in om deel te neem aan die navorsingstudie genaamd *"Functional thresholds as predictors of 20- and 40 km cycling performance"*.

Ek verklaar dat:

- Ek hierdie inligting en vrywaringsvorm gelees het, of dat dit vir my gelees is, en dat dit geskryf is in 'n taal waarin ek vlot of mee gemaklik is.
- Ek die geleentheid gegun is om vrae te vra, dat al my vrae is beantwoord is, en dat ek tevrede is.
- Ek verstaan ek neem **vrywillig** deel aan hierdie studie en dat ek geen druk ontvang het om deel te neem nie.
- Ek mag kies om my betrokkenheid by hierdie studie te staak ten enige tyd and dat niks slegs hiervan sal kom nie – ek sal nie te na gekom word of bevooroordeeld behandel word nie.
- Ek mag gevra word om my betrokkenheid by hierdie studie te staak voordat dit voltooi is, indien die studie doktor of navorser voel dis in my beste guns, of as ek nie die studie plan volg soos ooreengekom nie.

Geteken by (*plek*) ......................…........……………. op (*datum*) …………...……….. 2021.

| | |
|---|---|
| ........................................................................ | ............................................................... |
| **Handtekening van deelnemer** | **Handtekening van getuie** |

*Verklaring deur navorser*

Ek *(naam)* …………………………………………..……… verklaar dat:

- Ek die inligting in hierdie dokument eenvoudig en duidelik verduidelik het aan …………………………………..
- Ek hom/haar aangemoedig het om vrae te vra en genoeg tyd geneem het om hom/haar te antwoord.
- Ek tevrede is dat hy/sy volledig kennis geneem het van al die aspekte van die navorsingstudie soos bo bespreek.
- Ek 'n vertaler gebruik het/ nie gebruik het nie. (*Indien 'n vertaler gebruik is, moet die vertaler die onderstaande verklaring onderteken.)*

Geteken by (*plek*) .....................…........……………….. op (*datum*) …………...……….. 2021.

........................................................................ ..............................................................

**Handtekening van navorser** **Handtekening van getuie**

*Permissie om alle anonieme data met joernale mee te deel:*

Ons sal graag die resultate van hierdie studie in relevante joernale wil publiseer. Dit sal vereis dat ons anonieme data wat betrekking het met relevante joernale deel voordat die resultate gepubliseer word. Dus wil ons jou permissie verkry om jou anonieme data te deel met joernale.

**Dui asseblief jou opsie van permissie aan:**

Ek **gee** hiermee **permissie** om my anonieme data met joernale te deel vir publikasie doeleindes.

☐ Handtekening____________

OF

Ek **keur** hiermee **permissie af** om my anonieme data met joernale te deel vir publikasie doeleindes.

☐ Handtekening____________

*Permissie vir die deel van steekproewe en/of inligting met ander navorsers:*

Data wat versamel is deur hierdie studie mag aangevra word vir toekomstige studies. Dus wil ons die resultate wat verkry word deur hierdie studie, stoor, en deel met toekomstige navorsers. Ander navorsers wêreldwyd kan die resultate aanvra vir toekomstige navorsing. Om jou privaatheid te beskerm, sal jou naam vervang word met ‘n unieke numeriese kode. Al jou data sal gestoor word onder jou kode. Dus sal jou inligting anoniem bly. Ons sal ons bes doen om jou kode privaat te hou. Daarom wil ons graag jou permissie vra om jou data en inligting met ander navorsers te deel.

**Dui asseblief jou opsie van permissie aan:**

Ek **gee** hiermee **permissie** om my anonieme data met ander navorsers te deel.

☐ Handtekening____________

OF

Ek **keur** hiermee **permissie af** om my anonieme data met ander navorsers te deel.

☐ Handtekening____________

Appendix D: Borg Scale (RPE)

## RPE scale 6 – 20 (Borg, 1982)

Appendix E: Participant Training Questionnaire

# Training Questionnaire

Participant Code:…………………

| | | |
|---|---|---|
| How long have you been training for cycling as a sport specifically? | | |
| What type of cycling do you mostly do (i.e., road / MTB) | | |
| How many official races have you competed in over the past 2 years? | | |
| Are you currently being coached? | | |
| Please describe a typical week of your current training: | Duration (hours) | Intensity (1-10) |
| Monday | | |
| Tuesday | | |
| Wednesday | | |
| Thursday | | |
| Friday | | |
| Saturday | | |
| Sunday | | |
| What, on average, was the estimated number of hours you have trained per week over the past 6 weeks? | | |
| What, on average, is the estimated number of hours you have trained per week over the past 2 weeks? | | |
| What is the estimated intensity of your training over the past 6 weeks? | | |

# Appendix F: Calculations for Comparing Men *vs.* Women

| Coefficients of Variation | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $VO_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$) | PPO (W) | PPO ($W \cdot kg^{-1}$) | FTP (W) | FTP ($W \cdot kg^{-1}$) | CP (W) | CP ($W \cdot kg^{-1}$) | TT20 (min) | TT40 (min) |
| Men (n = 8) | 14.12 | 14.65 | 10.38 | 20.44 | 16.86 | 22.14 | 16.39 | 11.51 | 11.89 |
| Group (n = 13) | 14.33 | 21.78 | 11.89 | 27.53 | 18.43 | 26.84 | 16.62 | 10.98 | 10.99 |
| | | | | | | | | | |

| Independent Sample t-test | | |
|---|---|---|
| | t | p |
| $VO_{2max}$ | 1.77 | > 0.05 |
| PPO (W) | **4.6 | < 0.001 |
| PPO ($W \cdot kg^{-1}$) | *2.6 | <0.05 |
| Age | -1.60 | > 0.05 |
| Body Fat % | **-12.27 | < 0.001 |
| Weight | *4.08 | < 0.05 |
| Cycling Experience (yrs) | 0.95 | > 0.05 |
| Weekly training hours | 0.69 | > 0.05 |
| FTP (W) | *3.71 | < 0.05 |
| FTP ($W \cdot kg^{-1}$) | 2.22 | 0.05 |
| CP (W) | *3.15 | < 0.05 |
| CP ($W \cdot kg^{-1}$) | 1.87 | > 0.05 |
| TT20 (min) | *-4.12 | < 0.05 |
| TT40 (min) | *-2.48 | < 0.05 |