MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

„The Nature of Fatigue Development during High-Intensity Endurance Exercise Performance:

A Systematic Review and Approach of the Methodological Application of the Critical Power and Speed Concept"

verfasst von / submitted by

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"Erstens kommt es anders, zweitens als man denkt…".

Well, there is no quote that could describe the current situation and the year 2020 better than this well-known German saying, which has been often attributed to the poet Wilhelm Busch. Due to the worldwide pandemic this thesis had to undergo some modifications and I am happy that this worked out that well. So at this point I would like to thank my supervisor Dr. Christoph Triska, BSc MSc for adapting things to this special situation and for being so supportive and giving me a productive pastime during quarantine.

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ABSTRACT

Background: Since the discovery of the hyperbolic power-duration (P-D) relationship revolutionized the approach of endurance exercise, researchers try to advance its determination and make it easier to implement. For the latter, the 3-min all-out test (3MT) was applied to derive the parameters EP (end-test power) and WEP (work that can be done above EP), representing the so-called “Critical Power” (CP) and *W’*, the aerobic and the anaerobic parameters of the P-D relationship. Studies often show correlations and no differences between the “new” and conventional values, however, doubts arise when it comes to the question if they can be used interchangeably.

Objective: This thesis should summarize what is known so far when it comes to the P-D relationship, especially in terms of fatigue and the application of the 3MT and if (or how) it provides a useful tool to estimate the P-D parameters. Furthermore, it should give a methodological advice for the implementation into practice.

Review Methods: Data was searched up in PubMed by using the search strings “3 min all out test” OR “single all out test” AND “critical power” OR “critical speed” OR “critical velocity”. For the meta-analysis studies were included if they investigated the P-D relationship by using a 3MT and comparing this data to conventional derived CP and *W’* parameters. Gained information was processed in qualitative and quantitative ways. The methodological approach was conducted in running under laboratory and field conditions, by the application of a graded exercise test (GXT) and two 3MTs, one in rested and one in a fatigued condition (after 1.5 h of prior running). Determined P-D parameters were then compared to personal records (PR).

Results: There was no significant difference and a small effect size (ES) between 3MT and traditional CP values (ES = 0.16; 95% CI: -0.01 to 0.33; $p = 0.07$), but there was a significant difference and a moderate ES when comparing 3MT and traditional protocols in *W’* (ES = 0.62; 95% CI: 0.81 to 0.44; $p < 0.001$).

Conclusions: The results indicate that the 3MT is a valid way to determine CP. However, there were substantial differences in the determined *W’* values, leaving the recommendation that WEP and *W’* cannot be used interchangeably. Moreover, the physiological characterization of CP and *W’* may be different in a fatigued compared to a rested state.

ZUSAMMENFASSUNG

Einleitung: Seit die Entdeckung des hyperbolischen Zusammenhangs von Power und Zeit (P-D) das Verständnis von Ausdauerbelastungen revolutioniert hat, versuchen Forscher seine Erhebung und Implementierung zu verbessern und zu vereinfachen. Deswegen wurde der 3-min all-out test (3MT) eingeführt, von dem die Werte EP (end-test power) und WEP (work above EP) abgeleitet werden können, die wiederum die sogenannte „Critical Power“ (CP) und *W‘* repräsentieren (die aerobe bzw. anaerobe Komponente des P-D Zusammenhangs). Es gibt Studien die zeigen, dass zwischen den neuen und herkömmlich berechneten Werten Korrelationen und keine signifikanten Unterschiede bestehen. Jedoch treten auch Zweifel auf, dass man die Werte synonym betrachten kann.

Zielsetzung: Die Arbeit soll zusammenfassen, was bereits über den P-D Zusammenhang erforscht wurde. Im Speziellen wird die Verwendung des 3MT und dessen Validität geprüft, des Weiteren der Einfluss von Ermüdung auf seine Parameter. Zum Abschluss sollen methodologische Ansätze für die Implementation in die Praxis gegeben werden.

Methodik: In PubMed wurden die Suchbegriffe “3 min all out test” OR “single all out test” AND “critical power” OR “critical speed” OR “critical velocity” eingegeben. In die Meta-Analyse wurden jene Studien inkludiert, welche den P-D Zusammenhang durch das Einsetzen eines 3MT und im Vergleich mit konventionellen Methoden erforschten. Die gewonnenen Erkenntnisse wurden sowohl in qualitativer als auch quantitativer Weise ausgearbeitet und präsentiert. Der methodologische Ansatz wurde im Laufsport unter Labor- und Feldbedingungen durchgeführt. Dabei wurde zuerst ein Stufentest und anschließend wurden zwei 3MTs gemacht, einer in ausgeruhtem und einer in ermüdetem Zustand nach einer Vorermüdung von 1,5 h am Laufband. Die erhaltenen P-D Parameter wurden dann mit persönlichen Rekorden (PR) verglichen.

Ergebnisse: Es wurden keine signifikanten Unterschiede und eine kleine Effektstärke (ES) zwischen den von 3MT gewonnen und konventionell berechneten Werten in CP (ES = 0.16; 95% CI: -0.01 to 0.33; $p = 0.07$) festgestellt. Es gab aber signifikante Unterschiede und eine moderate Effektgröße bei der Erhebung von *W‘* (ES = 0.62; 95% CI: 0.81 to 0.44; $p < 0.001$).

Conclusio: Die Ergebnisse zeigen, dass der 3MT valide Werte für CP liefert. Jedoch wurden bedeutende Unterschiede in *W‘* festgestellt, was zur Schlussfolgerung führt, dass WEP und *W‘* nicht synonym verwendet werden können. Darüber hinaus hat eine Pilot-Testung gezeigt, dass der physiologische Charakter von CP und *W‘* unter Ermüdung beeinflusst wird.

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INTRODUCTION

Principles of Critical Power and its Determination

"How fast can I run some given distance?" Hill (1925)

Following this pervasive question and as far as sports and racing can be traced back, the ability of humans to endure a certain physical intensity is and has always been an object of fascination. Hill (1925), from whose article the opening question was cited, was the first to identify the hyperbolicity between exercise intensity and its sustainability. He did not only plot the statistical evidence of a given speed-time relationship, but also took account to ask for the "why" and underlying physiological principles. However, Monod and Scherrer (1965) were the first to formally describe the power-time relationship in a single-joint muscle action. This was followed afterwards by adapting the method for leg cycle ergometry (Moritani et al., 1981), running (Hughson et al., 1984) and other whole-body exercises, for review see: Poole et al. (2016).

Based on the findings mentioned above, the relationship between exercise intensity and time to task failure is hyperbolic and characterized by two parameters: (1) its asymptote, the so-called "critical power" (CP), or rather "critical speed" (CS) for exercise modes where speed rather than power is measured, and (2) the curvature constant, abbreviated as *W'* (for work; pronounced W prime) and *D'* (for distance), respectively. CP and equally CS demarcate a boundary between steady-state and non-steady-state exercise, whereas *W'* and by extension *D'* express the work that can be done above CP or alternatively the distance that can be covered above CS (Jones et al., 2019). For a better understanding and reading, except where noted otherwise, the terms CP and *W'* represent also CS and *D'*, as they can be seen interchangeably (Hughson et al., 1984).

One of the main applications of this mathematical concept is the monitoring and evaluation of performance, resulting into improved racing strategy and training prescription (Muniz-Pumares et al., 2019; Pettitt, 2016). Usually, the prescription of exercise intensities derived from metabolically parameters (turning points of lactate or gas exchange variables) and the duration of training loads were mostly set from experience and rarely prescribed by individual measurements (Hofmann & Tschakert, 2017). However, determining intensities relative to CP unites systemic and intramuscular responses and a specified, tolerable duration of exercise leading to desired training effects. Poole et al. (2016) designate CP as the "fatigue threshold", where exercise intensity below CP can and intensity above CP cannot be stabilized due to its specific physiological response. Thus, another important administration of CP is to demarcate the different intensity domains. Burnley and Jones (2018) outline where fatigue happens regarding the intensity prescriptions:

Below the lactate threshold (LT), in the moderate domain, fatigue develops slowly and mainly of central origin. Regarding the heavy domain (>LT but <CP), both, central and peripheral fatigue is observed and commonly correlated with the depletion of muscle glycogen. Intensity above CP, called the severe-intensity, is leading to progressive perturbation of muscle metabolic homeostasis increasing peripheral fatigue.

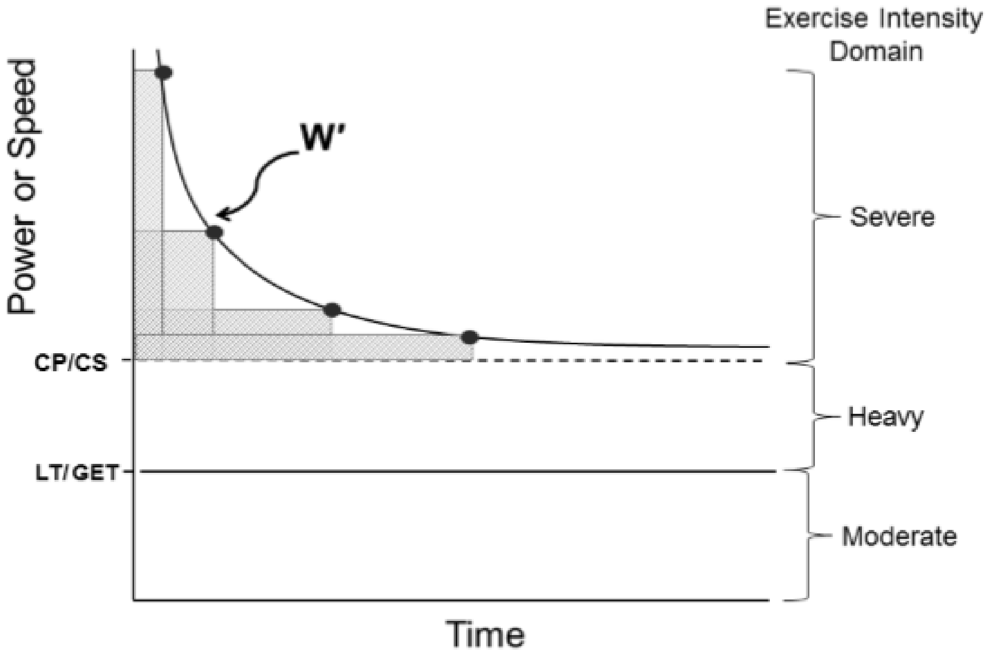


Fig. 1: The intensity domains and their respective boundaries (Poole et al., 2016).

The hyperbolic power-duration (P-D) relationship constructed by four constant power loads (dots) to the point of exhaustion, ranging between 2-15 min. The curve is defined by its two parameters: the asymptote as critical power (CP), demarcating a boundary between heavy and severe exercise intensity, and its curvature constant *W'*, denoted by the four rectangles and expressed in kJ. It is worth mentioning that all rectangles cover the same areas. In addition, one can see the lactate threshold (LT) or gas exchange threshold (GET) which can be defined during incremental or ramp exercises and which enable to distinct the moderate from the heavy domain.

However, the testing protocol for the determination of CP and *W'* has not yet been standardized. Constant work rate (CWR) tests to task failure are considered to be the "gold-standard" to determine the P-D relationship. This may be due to tradition, as it was also the first method to be proposed. Nevertheless, the number, duration and recovery-time between the tests affect the outcome and, moreover, make the procedure cumbersome (Muniz-Pumares et al., 2019). The determination of CP and *W'* by using time trials (TT) seems to be more practicable as the implementation of power-meters offers the possibility to test also in field in addition to laboratory conditions (Karsten, Jobson, Hopker, Jimenez, et al., 2014; Karsten et al., 2015; Triska et al., 2015). Furthermore, Pettitt (2013) states that in running, CS is commonly derived from personal records (PR) of different distances.

The implementation of a single all-out test, first proposed by Dekerle et al. (2006) and extended by Burnley et al. (2006), potentially constitutes a quick and simple alternative method for the determination of CP and *W'*. The theoretical basis therefore is in agreement with the mathematical description of the power-duration (P-D) relationship, which means that after *W'* is depleted, the residual maximally sustainable power output has to be equal to CP. As a matter of a fact, Vanhatalo et al. (2007) verified by the use of a single 3-min all-out test (3MT) that the end-test power (EP), representing the average power output over the final 30 s, can accurately depict CP and the amount of work done above EP power equates to *W'*. The 3MT has since then been applied for several other cycling studies, providing a valid and reliable estimation of the P-D parameters (Clark et al., 2018; Vanhatalo et al., 2007). However, some studies still question if the derived parameters really represent the "true" P-D parameters (Bartram et al., 2017; Bergstrom, Housh, Zuniga, Traylor, Lewis, et al., 2013; Bergstrom et al., 2014; Muniz-Pumares et al., 2019; Wright et al., 2017).

Pettitt et al. (2012) successfully transferred the 3MT into running to predict outdoor running performance. To note, no study before has directly assessed the accuracy of the parameter estimation comparing the 3MT in running to the traditional determination of CS and *D'*. Broxterman et al. (2013) point out, that the assessment accuracy is to be seen critical as there is a higher degree of variability when one compares treadmill to track running through a change in gait patterns which might vary the relationship between speed and actual muscular effort. Therefore, abovementioned authors showed that end-test speed (ES) did not significantly differ from the speed-time model CS and so does the distance above end-test speed (DES) when compared with *D'*, although the latter should be taken with caution as DES frequently underestimated *D'*.

Critical Power under the State of Fatigue

Performance diagnostics mostly occur under rested conditions. Quite recently, Clark et al. (2018; 2019b; 2019a) started to investigate the impact of fatigue on the parameters of the P-D relationship. Firstly, they showed that EP and WEP can be reliably determined from a 3MT after 2 h of heavy-intensity cycling. Secondly, when comparing the control 3MT to the fatigued one, EP and WEP were lowered in fatigued conditions (~10% and ~20%, respectively) which indicates a decrease of CP and *W'* as well. However, when testing maximum oxygen uptake ($\dot{V}O_{2max}$) in the fatigued state with intensity above EP it was lower than observed in an initial ramp incremental test before. When testing below that intensity, the majority of participants were unable to complete 20 min of exercise. Therefore, while the decline in EP after 2 h of heavy exercise is associated with impaired performance, the physiological and functional definition of EP appears to be different to that compared with EP tested in rest.

Clark et al. (2019a) found out that the changes in EP and WEP were not correlated to the reduction in muscle glycogen and conclude that this is an effect that might be related to low pre-test muscle glycogen. Another study (Clark et al., 2019b) shows that carbohydrate ingestion during exercise preserves EP and by extension CP without altering muscle glycogen. The authors suggest that, following prolonged endurance exercise, CP may be sensitive to global CHO availability via its relationship to central fatigue development, whereas *W'* may be sensitive to local muscle glycogen availability due to a limitation to energy production by anaerobic glycolysis.

These findings bring new insights into the physiology under fatigue conditions, providing a better understanding and even prediction of prolonged endurance exercise performance. Nevertheless, none of such studies has been conducted in the terms of running so far.

Rationale of the Thesis

Because of the underlying research gaps that arise, the present thesis deals with the following research questions:

- Does a 3-min all-out test for the determination of CP and *W'* prevent valid results? A systematic review and meta-analysis.
- Regarding CP in terms of fatigue conditions, what new explanatory power does it bring along and how can these findings be implemented into practice?
- What can be summarized when having a look at a single pilot testing suggesting a 3MT in running under fatigued conditions in comparison to rested condition and the estimated CS using personal records?

To answer these questions, this thesis is structured as follows:

In the first part of the thesis, a general overview concerning the background of CP and CS will be brought up. Then, theoretical principles of the determination and application of the P-D relationship and also physiology and fatigue pertaining to endurance exercise will be treated. Subsequently, a systematical research in the style of the guidelines of Liberati et al. (2009) and a meta-analysis dealing with the validity of the 3MT will be presented.

The third chapter deals with the inclusion of fatigue and a methodological approach of a potential follow-up study. Results of a single pilot study, the reproduction of the prolonged cycling study of Clark et al. (2018) into running, will be presented and discussed. Furthermore, practical implications will be given regarding and comparing "real" PR with both, fatigued and rested estimates of the CS. All statements will be discussed and summarized in the end of the thesis to prepare and suggest further investigations for future research and practical implications.

1 THEORETICAL PRINCIPLES OF THE POWER-DURATION RELATIONSHIP

1.1 Introduction

Historically, the connection between fatigue and performance was seen as something elusive (Poole et al., 2016). However, research beginning within the last century is bringing up evidence that it can be described by the means of the concept of a so-called “critical power”. Humanity was seeking for something logical, so that ongoing biological processes in the body can be described as something mathematically. Thus, several groups of researchers have successfully demonstrated the hyperbolic relationship between power and time to exhaustion in a variety of experimental situations. First proposed in cycle ergometry (Moritani et al., 1981), the mathematical modeling has also been successfully implemented in running (Hughson et al., 1984). Ever since then, the relationship between exercise intensity and time to exhaustion is making use of a number of different models and also terminologies as will be referred in the next chapter.

In cycle ergometry, exercise intensity can be measured in work rate or power. When talking about other exercise modes, like running for example, in this sense the terms speed and velocity are used. It should be stated that in the present thesis mainly the terms power and work will be mentioned, even when referring to speed, velocity or distance. Except where noted otherwise, CP and *W’* will also represent CS and *D’,* as they can be seen interchangeably (Hughson et al., 1984) and so that a better understanding and fluent reading is ensured.

Poole et al. (2016) point out that the P-D relationship mathematically describes but actually does not itself explain exercise tolerance. Therefore, besides enumerating the categorization of endurance exercise intensity (heavy, moderate, severe and extreme), it is important that they should also be seen in the light of fatigue and what that means in the sense of the P-D relationship. Furthermore, conventional approaches to determine CP and *W’*, CWR, TT, and the 3MT, as well as their limitations, will be explained.

1.2 Theoretical Background

In 1925, the British physiologist A. V. Hill turned out to be a pioneer in terms of the P-D relationship as he dedicated himself to the physiological basis of athletic recording. By plotting the relationship between average speed and the sustainable time of world record performances over a bandwidth of distances in running and swimming and including both, men and women, he showed that the relationship was inherent hyperbolic (Hill, 1925). As stated by Poole (2016), his findings remain evident when today's world records are plotted in the same torture. This seems to be of particular interest as it reveals that the P-D relationship is in its nature hyperbolic and not only when regarding one single individual. Hill set a solid foundation concerning the research of fatigue development in endurance exercise performance and gave important thought-provoking impulses, by asking for the "why" of the hyperbolicity and the "how" this might be applicable for practitioners. Both questions should be answered at a later date.

In 1965, Monod and Scherrer were the first to present the "Critical Power Model". In their sense, the CP of a muscle depicts the maximum rate of work that can be maintained "indefinitely" or for "a very long time without fatigue" (Monod & Scherrer, 1965). In addition to that, they proposed an "energy store", later to be called *W'*, that represented a limited amount of work that could be done above CP. The authors described the P-D relationship in a single-joint muscle action, afterwards the method was successfully adapted into endurance exercises like leg cycle ergometry (Moritani et al., 1981), running (Hughson et al., 1984) and other sport types like swimming and rowing (Kennedy & Bell, 2000; Wakayoshi et al., 1992). When having a look at different sport modalities and the number of studies publicized it can be seen that cycling is the most explored one.

No matter in which regard, Poole et al. (2016) summarize, by first being just a theoretical construct, the CP concept is now representing more than what it meant to be back then. In their review, the authors designate CP as the "fatigue threshold", where exercise intensity below CP (moderate and heavy exercise) can and intensity above CP (severe and extreme exercise) cannot be stabilized due to its specific physiological response. Fig. 1 summarizes and combines what has been investigated so far concerning the P-D relationship, such as its determination and demarcation of the different intensity prescriptions. In the case above, the determination of CP and *W'* has been done on the basis of four constant work to exhaustion bouts, however, the testing protocol is not standardized, and also the formulas to compute the parameters vary.

1.3 Determination of Critical Power and its related *W'*

For the determination of the P-D parameters the traditional approach constitutes the performance of 3-5 CWR tests in a laboratory setting with a duration spanning from 2 to 15 min (Muniz-Pumares et al., 2019; Poole et al., 2016). There, the power output (PO) (W) and the time to task failure (T_{lim}) (s) are recorded during each test. On that basis, one can calculate the total work that is done (Work = PO x T_{lim}) and the inverse of T_{lim} (T_{lim}^{-1}). Following this data, diverse mathematical models can be applied to estimate the P-D parameters (Gaesser et al., 1995).

1.3.1 Estimation of Critical Power and *W'*: Modeling Performance

Mathematically, the hyperbolic relationship between PO and endurance can be described by using the following equation (Gaesser et al., 1995):

$$T_{lim} = W' / (PO - CP) \qquad \text{(2-parameter nonlinear/hyperbolic)} \qquad [1]$$

Here, CP is presented by the asymptote of the hyperbola and the curvature constant depicts *W'*. T_{lim} is determined by any given PO above CP. Equation 1 may be linearized by plotting PO against the inverse time. In this sense, the y-intercept represents CP and W' is presented by the slope (Moritani et al., 1981):

$$PO = CP + W' \times T_{lim}^{-1} \qquad \text{(2-parameter linear (PO))} \qquad [2]$$

Alternatively, another linear expression depicts CP as the slope and W' as the y-intercept by plotting the work against time achieved from each CWR (Monod & Scherrer, 1965):

$$Work = W' + CP \times T_{lim} \qquad \text{(2-parameter linear (Work))} \qquad [3]$$

Regarding the 2-parameter models, whether nonlinear or linear, Gaesser et al (1995) indicates a certain limitation: If T_{lim} approximates zero, PO becomes infinite. Therefore, Morton (1996) inserted a third parameter, *k,* standing for the maximal instantaneous power (PO_{max}):

$$T_{lim} = (W' / (PO – CP) + k$$

$$T_{lim} = (W' / (PO – CP) + (W' / (CP – POmax) \qquad \text{(3-parameter model)} \qquad [4]$$

At this point it should be mentioned that, beyond the four equations above, there are numerous of further models establishing CP and *W’*, such as the exponential ones by Hopkins et al. (1989) and Peronnet and Thibault (1989) in running (for review see: Sreedhara et al. (2019)). The relevance of the models in relation to the present thesis is limited to these four as they are the ones to be most frequently used and representing CP and *W’* the most accurate (Muniz-Pumares et al., 2019). Additionally, they have been successfully proven in determining CS as well as *D’* (Hill et al., 2011), so all equations can be used interchangeably (CP becomes CS, *W’* becomes *D’*, PO is to be substituted by speed and work by distance).

Unfortunately, the question of which one to use stays unresolved (Muniz-Pumares et al., 2019). However, there is an advance towards using the 2-parameter models, as the 3-parameter protocol (1) requires a higher number of trials making it more cumbersome to use (Morton, 1996), (2) often produces nonphysiological estimates of maximal power outputs, (3) consistently results into lower estimates of CP and higher values for *W’* and (4) the intersubject variability appears to be large, so summarized by Muniz-Pumares et al. (2019). Therefore, the authors give the recommendation that the P-D parameters should be characterized with the 2-parameter model that causes the lowest standard error of estimate (SEE).

1.3.2 Constant Work Rate Tests to Task Failure and Time Trials

Laboratory-based protocols normally are constituted as open-end tests with constant work rate (CWR), whereas field testing instead typically employs maximal effort over a given time or distance, called time trials (TT) (Muniz-Pumares et al., 2019). These authors state that the test-retest reliability of the P-D parameters gained from CWR seem to be a problematic issue as the coefficient of variation (CV) and the correlation coefficient (*r*) of CP lay at 3% and 0.96, and for *W’* within ~10% and 0.79, respectively (using the linear equation 2).

At this point it is important to note that the large variation in *W’* seems to be defined by the formula that is used. Although being mathematically evident, equations 1-3 often lead into different assumptions of the parameters (Bergstrom et al., 2014; Bull et al., 2000; Gaesser et al., 1995). However, Triska et al. (2015) on the other hand proved that there were no significant differences between all three mathematical models for CP and *W’* (for review also see: Muniz-Pumares et al. (2019)). Additionally, the same authors state that there is a variability of 10-15% in T_{lim} observed in CWR and no matter which methodological approach is followed, it seems that the test-retest reliability for *W'* is always poorer than that for CP. *W'* appears to vary greatly, but however, both parameter seem to have a high reliability when tested in TT. Moreover, a familiarization trial seems to increase reliability (Triska et al., 2017b).

It is not only the modality, but also the model, the duration and the number of the predictive trials, as well as their resting time in between, that affect CP and *W'*. It can be concluded that the duration should lie in between 2-15 min and that $\dot{V}O_{2max}$ should be attained. Two trials may be enough but at least three or better more trials should be done for research purposes to target reliable values (Muniz-Pumares et al., 2019; Triska et al., 2015). Triska et al. (2015) prove that for an easy integration into the training process three prediction trials can be done in a single training session within 2 h and therefore offer a time-saving method that could be integrated into training whenever position of performance is warranted. Moreover, Simpson and Kordi (2017) obtained reliable CP and *W'* parameters using only two maximal-exercise trials in a single session.

1.3.3 3-Minute All-Out Test

As described above, lots of progress is made talking about the practicability and the estimation of P-D parameters when regarding it from the perspective of the inclusion of a training process. When having a look into research conditions, it is necessary to keep something reproducible to ensure comparability (for example to test the efficacy of an intervention) and to keep the period short. What if one single all-out test was enough to obtain the parameters of the P-D relationship?

Based on the fact that at the beginning of an all-out effort *W'* may be heavily used and maintaining the exercise would lead into a fully depletion what moreover leads into a PO representing CP, Dekerle et al. (2006) were the first to ask themselves this question. Their chosen duration of 90 s seemed to be too short as PO at the end of the test was greater than CP, providing indication that *W'* was not fully used up. The ones who brought up the answer and evidence that the assumption was right were Burnley et al. (2006) as they extended the duration to 180 s. They noticed that the reduction in PO had reached a plateau in the last 30 s of the test and defined it as EP.

In a follow-up study, Vanhatalo et al. (2007) reported a very close connection between the conventionally determined CP and the EP attained during a 3MT (r = 0.99; SEE = 6.4 W). Similarly, WEP was comparable with *W'* (r = 0.84; SEE = 2.6 kJ).

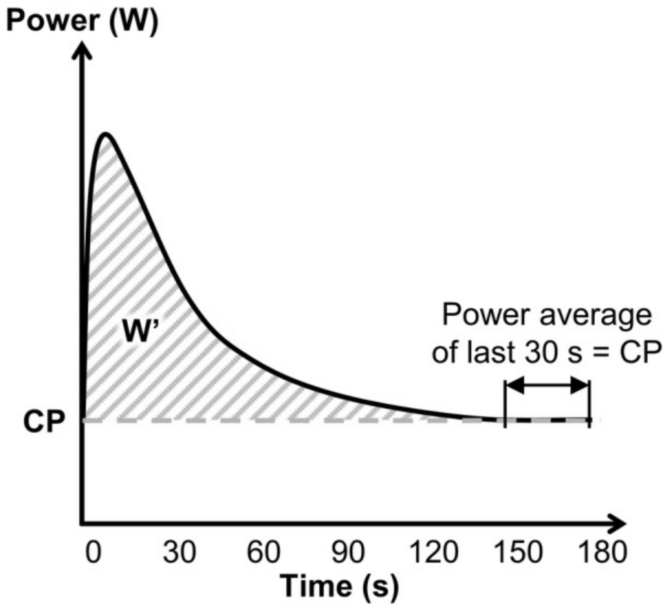


Fig. 2: Schematic representation of a 3-min all-out test (Sreedhara et al., 2019).
The typical curvilinear power profile with the last 30 s (EP) representing CP and the area above CP and below the curve depicting *W'* (WEP). True all-out effort is guaranteed if PO reaches a plateau in the last 30 s and peak PO is attained within the first 10 s.

Although the parameters of the P-D relationship can be derived from only a single test, the original 3MT of Burnley et al. (2006) and Vanhatalo et al. (2007) still requires two separate testing visits, as the gas exchange threshold (GET), preferred cadence and $\dot{V}O_{2max}$ must be defined by a preliminary graded exercise test (GXT). The testing procedure starts with unloaded cycling, resulting into the instruction that the participant should accelerate to a cadence up to 110-120 rpm. Reaching that point, the cycle ergometer immediately switches into a linear mode, described by following equation:

$$\text{Linear factor} = \text{PO at } \Delta 50\% \times \text{Cadence}^2$$

The factor is set that at the participant's preferred cadence, PO corresponds to halfway between GET and $\dot{V}O_{2max}$, which is proposed to approach to CP (Burnley et al., 2006).

Correspondent to the considerations of the authors mentioned previously, Muniz-Pumares et al. (2019) summarize the following criteria to ensure a true all-out effort in the 3MT:

(1) PO should reach a plateau in the last 30 s of the test; (2) peak PO should attain in the first 10 s of the test; (3) after peak value, there should be a rapid initial decrease in PO; (4) EP should not fall > 5% for > 5 s; (5) end-test cadence should stay within 10 rpm of preferred cadence; (6) $\dot{V}O_{2max}$ must be attained; and (7) blood lactate concentration should be above 8 mmol/L. In addition, to avoid pacing, participants are blinded to the elapsed time.

To shorten the procedure, several authors tried to simplify the 3MT, like Johnson et al. (2011) and Bergstrom et al. (2012) for instance, who suggested to determine the resistance relative to the body mass so that no prior test is needed to detect the GET and $\dot{V}O_{2max}$. The latter suggested that a modified 3MT with a resistance set at 4.5% of body mass, implemented on a mechanically braked ergometer, can successfully determine EP and WEP. Similarly, Clark et al. (2013) were using loads of 3, 4 or 5% of body mass, depending on fitness status, and all resulting into similar values of EP and WEP when compared to values derived from the 3MT using the linear factor of 50%Δ and so did Dicks et al. (2016). When having a look at the reliability of EP and WEP, both parameters show similarities compared to CP and *W’* derived from conventional testing approaches. It does not come as a surprise that EP also seems to have a better CV (3-7%) than the WEP (8-21%) (Burnley et al., 2006; Dicks et al., 2016; Johnson et al., 2011; Muniz-Pumares et al., 2019).

However, other approaches have also been adopted to determine CP and *W’* using a 3MT, including sports like running (Clark, West, et al., 2013), rowing (Cheng et al., 2012), swimming (Courtright et al., 2016), cross-country skiing (Fukuda et al., 2014) and team sporting (Polglaze et al., 2018).

1.4 Application of Critical Power and *W'*

CP and *W'* seem to be of particular interest to researchers, coaches and athletes. Regarding aerobic endurance exercise, especially CP is an important parameter as it demarcates the boundary between steady and non-steady state, leading into a simplification and a more homogenous response for the normalization of intensity prescription (in contrast to other approaches like, for example, the percentage of $\dot{V}O_{2max}$) (Lansley et al., 2011; Muniz-Pumares et al., 2019).

On basis of knowing the domains derived from the concept, time to task failure can be predicted. In their review, Muniz-Pumares et al. (2019) state that CP has been proven to account for sporting events lasting from about 2 to 59 min. CP is not only significantly related to time to exhaustion, but it is also shown to predict race paces and exercises taking place beyond laboratory conditions, like shown by Kranenburg and Smith in running (1996) when they compared track-determined CS to 10 km race speed and by Black et al. in cycling (2014) as the CP derived from a 3MT predicted 16.1 km road TT. Additionally, according to Nimmerichter et al. (2017), a combination of the use of CS and *D'* is valuable for predicting performance over race distances of 5,000 m as the accuracy is within ~1%. In terms of running events lasting longer than one hour, talking about a marathon, Florence and Weir (1997) demonstrated strong correlations to CS. According to Jones et al. (2010) and Vanhatalo et al. (2011), mean speed sustained by elite marathon runners lies within the “heavy” intensity domain (~96% of CS). When investigating running activities of recreational athletes, Smyth and Muniz-Pumares (2020) found out that estimations of CS from raw training data can successfully predict marathon performances.

As the P-D relationship provides insight into the capability of endurance exercise performance, Puchowicz et al. (2018) recently suggested that the model could be a useful tool for doping detection, but more research is necessary to successfully adopt it into this field.

Jones and Poole (2009) indicate that testing CP is a well suited method for an assessment of endurance exercise performance because it is reliable, valid, objective, accurate and noninvasive. Beyond that, from the physical performance done, physiological determinants can be derived. The testing procedure can easily be integrated into training and to apply the traditional testing, nothing else is needed than the mathematical model to compute the P-D relationship. A very common and often used tool therefore is the freeware GoldenCheetah, which can import data recorded from devices (such as the ride data of cyclists) and provides a rich set of analysis tools, for more details see: https://www.goldencheetah.org/.

At this point it should be noted that the P-D relationship describes but does not itself explain exercise tolerance and so the next chapter should beyond a description give an insight into fatigue process.

1.5 Physiology and Fatigue: The Limits of Human Performance

Burnley and Jones (2018) state different terminologies when it comes to the limit of human performance due to a constant power exercise. The moment at which one is unable to endure a physical task can either be seen as the point of "exhaustion", the point of "fatigue", or the "limit of tolerance". Additionally, they advise to use the term "task failure" as the task itself, and also the cause for failing to continue it, can be well explored. The same authors conclude that maximal neuromuscular effort can only be hold up for at least a few seconds. On the contrary, if the power or speed requirement is low, the capacity to maintain the task is high so that exercise can be continued for many hours (Davies & Thompson, 1986; Martin et al., 2010). But not just to regard these two extremes, it is of particular interest to address the sustainable power output that declines in between in its characteristic curvilinear pattern.

As the P-D relationship has been well described in a mathematical way, it should now be seen in a broader sense, in terms of fatigue. For that matter, the exercise intensity domains as presented in the review of Burnley and Jones (2018) will be established regarding the P-D relationship and its metabolic and physiologic responses.

1.5.1 Intensity Domains, Respective Boundaries and Respiratory and Metabolic Responses

Four intensity domains have been investigated and defined so far regarding their respective responses. They designate the degree and for that reason the effect of fatigue experienced (Burnley & Jones, 2018; Jones & Poole, 2009). Originally, Gaesser and Poole (1996) described three exercise intensity domains: moderate, heavy and severe as can be seen in Fig. 3.

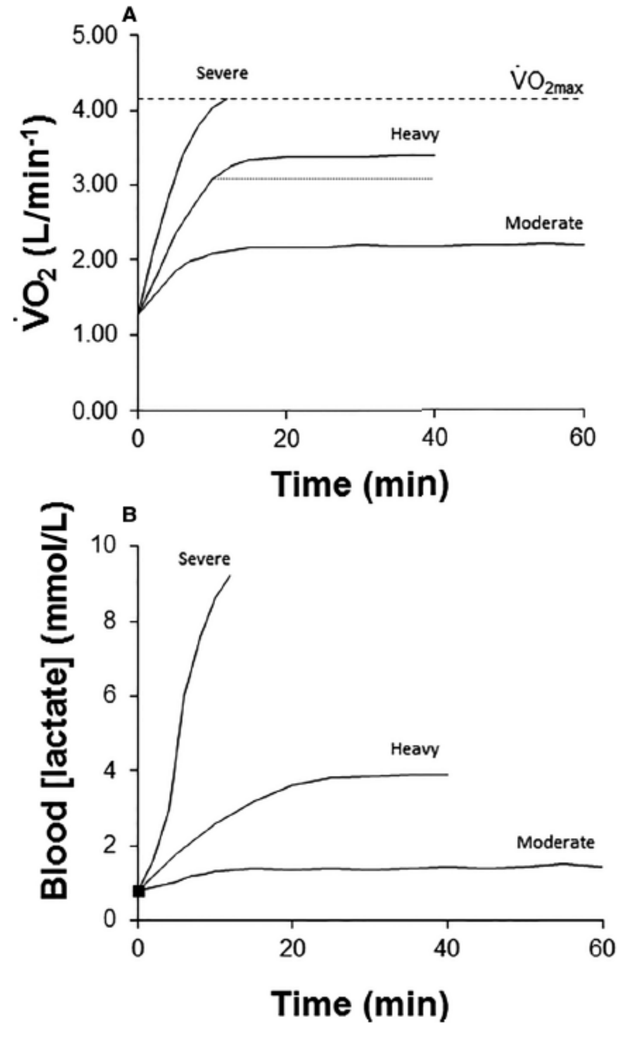


Fig. 3: The intensity domains and their respiratory and metabolic responses (Jones et al., 2019).

Panel A shows the chronological trend of the pulmonary oxygen uptake ($\dot{V}O_2$) when maintaining a certain intensity: It depicts the so-called "slow-component" in the heavy domain and the attainment of $\dot{V}O_{2max}$ in the severe domain. Panel B displays the metabolic responses regarding the blood lactate concentration: In the moderate domain the concentration stays akin to those in resting state, in the heavy domain it reaches a steady elevated level and in the severe intensity there is no steady-state possible (Burnley & Jones, 2018).

These intensity domains are demarcated through the lactate threshold (LT), or rather the gas exchange threshold (GET) or ventilatory threshold (VT), and the CP, or also through the respiratory compensation point (RCP).

1.5.1.1 The first Threshold: Anaerobic Threshold, Gas Exchange Threshold, Ventilatory Threshold or Lactate Turnpoint 1

There are various ways and definitions to describe the first threshold. However, one thing all determinations have in common is that they separate the moderate from the heavy intensity domain. The first threshold defines the first disproportionate increase in carbon dioxide output relative to oxygen uptake, with an increase in the ventilatory equivalent for O_2 ($\dot{V}E/\dot{V}O_2$), but no increase in the ventilatory equivalent for CO_2 ($\dot{V}E/\dot{V}CO_2$) (Beaver et al., 1986).

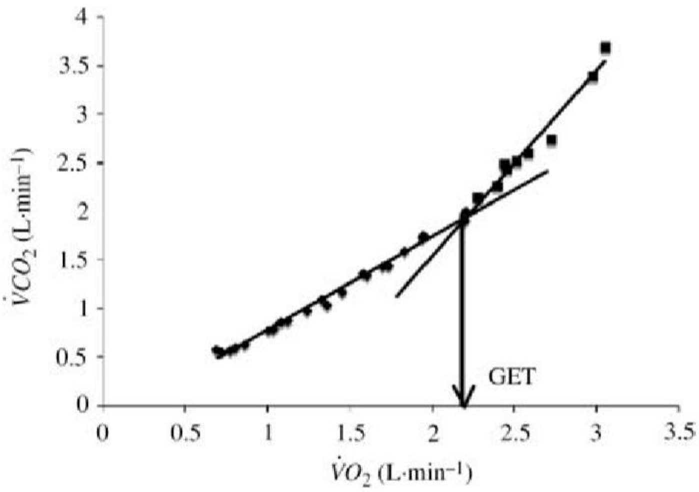


Fig. 4: Gas Exchange Threshold (GET) determination via the $\dot{V}CO_2/\dot{V}O_2$ relationship (Bergstrom, Housh, Zuniga, Traylor, Camic, et al., 2013)

In Fig. 4 one can see the determination of the gas exchange threshold (GET), using the V-slope method first described by Beaver et al. (1986). There, the GET is defined as the $\dot{V}O_2$ value corresponding to the intersection of two linear regression lines, which are derived separately from data points below and above the breakpoint according to the $\dot{V}CO_2/\dot{V}O_2$ relationship.

Fig. 5 shows the determination of the ventilatory threshold (VT) using two visual inspection criteria to locate it: 1) the $\dot{V}E/\dot{V}O_2$ curve has its point of increase as the $\dot{V}E/\dot{V}CO_2$ curve remains constant or decreases; and 2) the partial pressure of end-tidal carbon dioxide (PET_{CO2}) in relation to $\dot{V}CO_2$ curve remains constant and the partial pressure of end-tidal oxygen (PET_{O2}) in relation to $\dot{V}O_2$ curve begins to increase (Beaver et al., 1986).

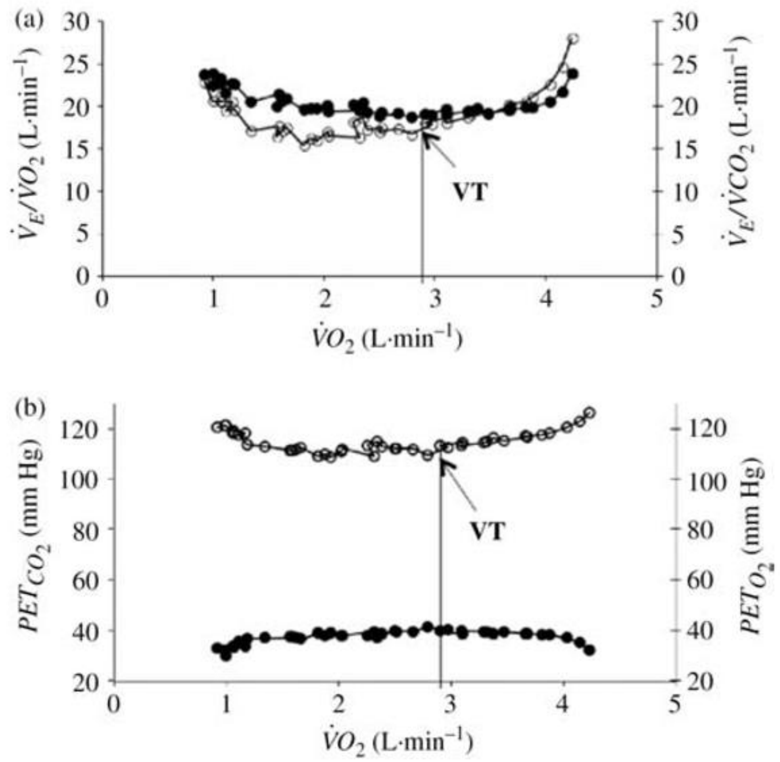


Fig. 5: Ventilatory Threshold (VT) determination via two criteria: (a) $\dot{V}E/\dot{V}O_2$ curve (open circles) and $\dot{V}E/\dot{V}CO_2$ curve (closed circles) and (b) $PET_{CO2}/\dot{V}CO_2$ curve (closed circles) and $PET_{O2}/\dot{V}O_2$ curve (open circles) as presented by Bergstrom et al. (2013).

Moreover, the first lactate turnpoint (LTP1) is defined as the moment when lactate concentration first continuously rises above baseline level (Smith & Jones, 2001), which also is a sign that the heavy intensity is reached.

1.5.1.2 The second Threshold: Respiratory Compensation Point or Lactate Turnpoint 2

As the first threshold is mainly relevant for ultra- and low-intensity endurance events, the second boundary is of more relevance for this thesis, as it is said to be in direct relation with CP. The respiratory compensation point (RCP) depicts the $\dot{V}O_2$ value corresponding to the point of departure from linearity of the VE/VCO_2 relationship (Beaver et al., 1986), which can be seen in Fig. 6.

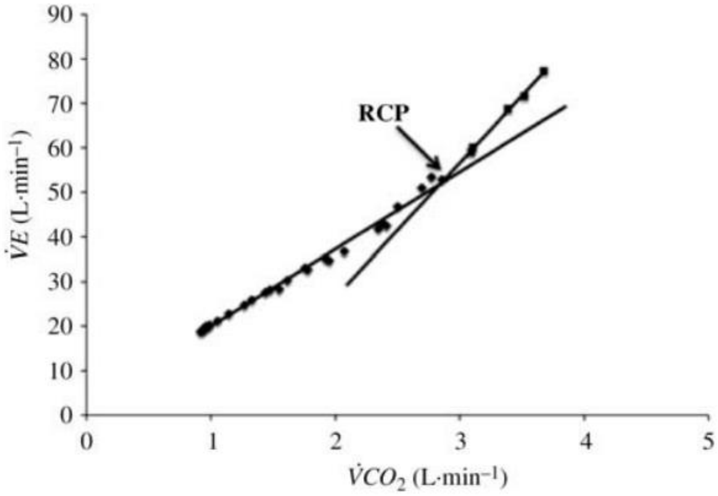


Fig. 6: Respiratory Compensation Point (RCP) determination via the VE/VCO_2 relationship by Bergstrom et al. (2013).

In terms of lactate, the second lactate turnpoint (LTP2) is defined as the point of a sudden and sustained increase in blood lactate (Smith & Jones, 2001).

1.5.1.3 Further Investigations

Beyond the thresholds and mentioned domains, Hill et al. (2002) were the first to bring up the importance of an additional, supra-severe exercise domain, as time to task failure occurs to be shorter than predicted by the severe intensity power-duration relationship when reaching such great exercise intensity outputs. Therefore, the "extreme-intensity" was dubbed. It represents power outputs that quickly lead into task failure before $\dot{V}O_{2max}$ can be attained. In this domain, questions arise that cannot be fully answered to this date. It has been well explored that energy stores can be depleted and backfilled, however, when it comes to the inclusion of this phenomenon into the P-D relationship, more successful research regarding this is warranted (Sreedhara et al., 2019).

Of more relevance for this thesis is intensity that is located around the "second boundary" or "second threshold", represented as RCP, CP or VT2 and LTP2. Most types of high-level endurance exercise performance take place at 75-90% $\dot{V}O_{2max}$, talking about the range between heavy and severe intensity (Jones et al., 2019). Regarding this, the sharper focus will be on the intensity domains around the CP.

Interestingly, Ozkaya et al. (2020) indicated recently that there might be a “grey zone” between the heavy and severe exercise domains. They determined a “critical threshold” (CT) interpreted as *“the highest exercise intensity where $\dot{V}O_2$ can be stabilized before reaching 95% of $\dot{V}O_{2max}$”* to compare it with commonly used anaerobic threshold indices: the VT determined from an incremental test, mathematically modeled CP from CWR, and the maximal lactate steady state (MLSS) detected by a 30 min constant-load exercise.

The widely used definition describes the MLSS as *“the power output at which the increase in blood lactate is less than 1 mmol/L between 10 and 30 min of exercise”* (Jones et al., 2019). In their review, Jones et al. (2019) indicate that MLSS happens at power outputs under the CP.

In the study of Ozkaya et al. (2020) results showed that work rates corresponding to CT was significantly greater ($p = 0.000$) than that of the MLSS, VT and CP, and there was no significant difference ($p = 0.621$) in $\dot{V}O_2$ between the 10^{th} and 30^{th} min of MLSS. Exercising $\dot{V}O_2$ response of MLSS + 15 W exercise could not exceed the level of 95% $\dot{V}O_{2max}$, whereas $\dot{V}O_2$ responses exceeding the 95% $\dot{V}O_{2max}$ were always attained during exercise done at CT + 15 W. Therefore, the authors state a gap between the heavy and severe exercise domain.

Galán-Rioja et al. (2020) took up the controversy concerning the proximity of CP and any metabolic and ventilatory threshold and performed a meta-analysis to show up the degree of correspondence or the difference, respectively, between CP and MLSS, VT1, VT2 and the RCP. On average, in their selected studies the PO at CP has been reported to be 30% higher than in the VT1, 11% higher than the MLSS, 6% lower than in the RCP and 21% lower than in the VT2 (Fig. 7). Although significant correlations were found between CP and VT1 ($r = 0.76$, $p < 0.001$), MLSS ($r = 0.77$, $p < 0.001$) and RCP ($r = 0.80$, $p < 0.001$), high coefficients of variation (CV) support the assumption that the same threshold intensity is not being measured. They conclude that CP can be determined with relatively little error and that MLSS, VT2 and RCP may all be secondary manifestations of CP. Their methods of determination (for example ramp versus CWR) and detection may be biasing the proximity to CP.

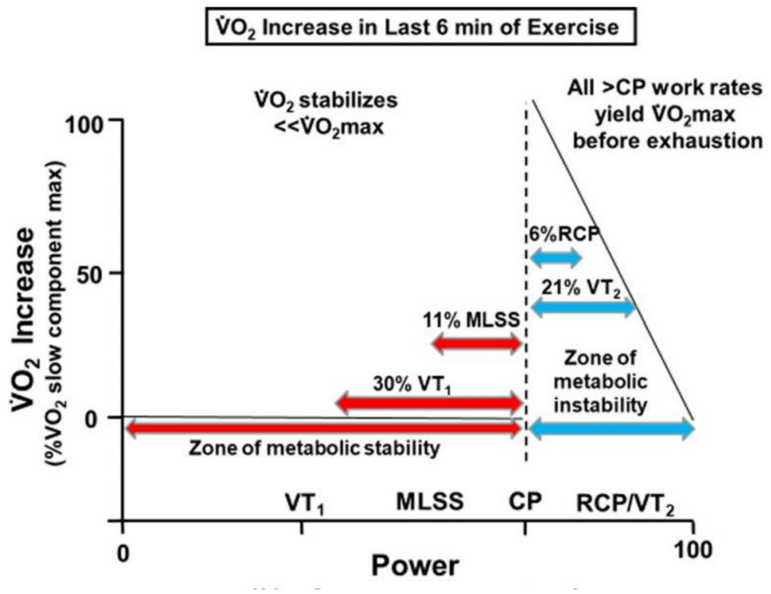


Fig. 7: Relative proximity of ventilatory/metabolic thresholds and CP regarding $\dot{V}O_2$ increase in the last 6 min of exercise bouts versus power (Galán-Rioja et al., 2020).

Moreover, Pethick, Winter and Burnley (2020) brought up physiological evidence that the CP is more a phase transition than a threshold. The authors monitored muscle O_2 uptakes, electromyograms and torque variabilities and complexities throughout different exercise tasks in close proximity to the critical torque (CT) and found out that the transition between the heavy and severe-intensity occurs gradually and not suddenly.

1.5.2 Fatigue during Exercise below Critical Power

Theoretical and as can be seen when having a look at the shape of the hyperbole of the P-D relationship, exercises at an intensity domain below the CP, including moderate and heavy exercises, are said to be maintained indefinitely long. However, scientific findings are equivocal. Although the physiological responses seem to be detected easily, the ongoing fatigue processes and mechanisms that are limiting factors are difficult to separate. Talking about the moderate domain, Burnley and Poole (2018) indicate the lack of exhaustive exercise data in this intensity as it could be done for a duration exceeding several hours and hence most of the time they are terminated before task failure arises. By contrast, the heavy-intensity domain is well-examined.

1.5.2.1 Moderate Intensity Domain

"Moderate intensity" is defined as the zone where power outputs occur below the LT or GET. This domain is the only one in which a steady-state is attained within the first 2-3 min of exercise. The blood lactate in moderate intensity stays akin to those in resting state (Jones et al., 2019).

A negligible number of ultra-endurance studies investigating physiological responses, giving an insight into fatigue processes during very prolonged exercise tasks. Davies and Thomson (1986) for example studied 10 ultramarathon runners when running 4 h on a treadmill at the highest pace they could sustain, estimating to be between 65-70% $\dot{V}O_{2max}$. The blood lactate levels and respiratory exchange ratios (RER) of the participants remained at the resting levels throughout the testing, conforming that the exercise was done in the moderate domain. However, the pulmonary $\dot{V}O_2$ response did successively rise during the performance, what leads to the assumption that the increase in O_2 cost could be compared to the $\dot{V}O_2$ slow component associated with the heavy exercise domain, as being similar in its amplitude although developing much more slowly (Burnley & Jones, 2018; Gaesser & Poole, 1996).

According to Gollnick et al. (1974), this increased energy expenditure during progressed exercise is due to muscle bioenergetics and/or motor unit recruitment shifts that were needed to maintain the task. Davies and Thompson (1986) suggest that, for example, $\dot{V}O_2$ will also grow during prolonged exercise to some extend because of the alteration towards the use of fatty acids, as they have a lower power output ratio when comparing to carbohydrates. Nevertheless, the fact that most of the increase in $\dot{V}O_2$ appears to be a result of neuromuscular fatigue has been proven several times: Davies and Thompson (1986) found a 25% loss in maximal voluntary contraction (MVC) force with no alteration in tetanic force output in response to peripheral stimulation, so that it can be ascribed to central origin. Martin et al. (2010) acknowledged the predominance of central fatigue induced by a 24-h-treadmill run, and so did Lepers et al. (2002) in 5 h of cycling.

1.5.2.2 Heavy Intensity Domain

Power output that is located between the LT or GET and the CP is named "heavy". In this domain, time to task failure is in-between the range of ~40 min and ~3 h and power outputs range from 60-85% $\dot{V}O_{2max}$ (Burnley & Jones, 2018; Coyle et al., 1986). The physiological characteristics of this domain are the development of the $\dot{V}O_2$ slow component as well as the rise in blood lactate, and their stabilization as exercise intensity continues (Jones & Poole, 2009). According to Burnley et al. (2012) both, global and peripheral fatigue, seem to play a role in the heavy intensity exercise domain. The authors indicate that, although happening much slower than in comparison with severe-intensity, peripheral fatigue is in progressive development. This could be attributable to multiple processes, with the depletion of muscle glycogen depicting the main reason (Burnley & Jones, 2018; Coyle et al., 1986). The authors explain, that because of the $\dot{V}O_2$ slow component, O_2 cost gets higher and this again causes that energy reserves of the body (mainly in the form of muscle glycogen) are required at a greater rate.

Regarding central fatigue, maintaining heavy power exercise leads to increased central motor drive. This is happening due to the repeating activation, as the motoneurons require stronger excitatory inputs to maintain the firing rates (Johnson et al., 2004). Combining both peripheral and central processes is giving an idea of what factors there are limiting to sustain a heavy task. It is of importance to notice that no mechanism by itself can explain neuromuscular fatigue and, by extension, exercise intolerance and that task failure is always subject to a constant interplay of ongoing processes.

1.5.3 Fatigue during Exercise above Critical Power

According to Burnley and Jones (2018), exercise that is done above the CP is endurable for less than ~40 min. However, time to task failure depends on how the curvature, talking about *W'*, of the P-D relationship is shaped, or more specifically, the time to task failure can be predicted with the equations in chapter 1.3. Since the asymptote CP is said to demarcate the boundary between steady and non-steady state, the principal characteristic of the intensity above CP is that responses of $\dot{V}O_2$, blood lactate concentration, as well as muscle metabolism, cannot be stabilized any longer (Jones et al., 2019; Jones et al., 2008). What is also crucial is the fact that in the severe-intensity domain the $\dot{V}O_2$ slow component rises until the attainment of $\dot{V}O_{2max}$, which happens close to the moment of task failure (Jones & Burnley, 2009).

Interestingly, the development of the $\dot{V}O_2$ slow component increases as the power demand is increased above CP, whereas its amplitude decreases and therefore it is the trajectory of the $\dot{V}O_2$, or the kinetics, respectively, which best depicts fatigue in any domain above CP (Burnley & Jones, 2018). Comparably to that, as contractile intensity is increased above CP, the loss in muscle phosphorylcreatine (PCr), pH, and the rise in Ca^{2+}

handling show up an acceleration, but reach consistent values at task failure (Burnley & Jones, 2018; Vanhatalo et al., 2010).

According to Burnley et al. (2012), peripheral fatigue also shows up an inexorably development, leading into the conclusion that the behavioral similarities between muscle and pulmonary $\dot{V}O_2$ kinetics, muscle substrate and metabolite alterations, as well as peripheral fatigue show up a mechanistic connection (Poole et al., 2016) and also underpin the hyperbolic character of the P-D relationship itself (Burnley & Jones, 2018).

1.5.3.1 Severe Intensity Domain

Burnley and Jones (2018) summarize that a severe-intensity exercise demand is resulting into a strong loss of the muscle metabolic homeostasis, which directly impairs muscle power output. That again requires supplementary motor unit recruitment and leads into increasing the O_2 cost of exercise. Therefore, task failure in the severe-intensity is likely to be the result of a mismatch between the power that is demanded and its instantaneous supply by the neuromuscular system. Following that, the mismatch is involving multiple interacting mechanisms, which differ from those at lower intensities. As the intensity increases, the relative importance of peripheral factors seems to increase (whereas in decreased intensity, it is more likely that the central and psychological factors play a more important role).

1.5.3.2 Extreme Intensity

Hill et al. (2002) introduced an “extreme” domain, where time to task failure would typically be reached less than about 2 min, but $\dot{V}O_{2max}$ will not be attained. Alexander et al. (2019) show that the P-D relationship of this domain is likewise hyperbolic, but cannot be linked to the mechanisms for fatigue and task failure for intensities below, as the mechanisms limiting extreme intensity may be able to fully recover within 90 s following exercise termination.

Sreedhara et al. (2019) review models that include the addition of recovery to the two-parameter model (Morton & Billat, 2004; Skiba et al., 2015) but conclude that this is an area where an improvement for the accuracy of the recovery of *W’* is needed.

2 VALIDITY OF THE 3-MIN ALL-OUT TEST – A SYSTEMATIC REVIEW AND META-ANALYSIS

The "Gold Standard" to determinate the P-D relationship is said to be the traditional model, defining the two parameters CP and *W'* from 3-5 CWR computed by using one of the 2-parameter equation (Muniz-Pumares et al., 2019). Since the 3MT has been introduced, more and more researchers take advantage of its simple and practical usage (Pettitt et al., 2019). However and as well explained above, still the validity of the gained parameters EP and WEP remain an area of concern. To date, this discrepancy has not been investigated in a systematical way before.

Due to the research gap that is coming up, this part of the thesis deals with the following research question:

- Does a 3-min all-out test for the determination of CP/CS and *W'/D'* prevent valid results?

In order to validate the "new" values derived from a 3MT, EP as the aerobic and WEP as the anaerobic parameter, Muniz-Pumares et al. (2019) indicate to compare them to those derived from the traditional way. Therefore, to answer the research question, a systematic search of literature in reference to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009) was conducted and will be presented.

2.1 Methods

2.1.1 Eligibility Criteria

Since it is a fairly recent topic, or rather a topic of increasing interest, no publication date restriction has been imposed. All studies were eligible for inclusion if they met the following criteria:

- comparison of a 3MT with the traditional method either using TTE or TT
- no interventions or supplementations or other comparatistics like hypoxia or heat

- males and females of any age and activity level ranging from physically active to well-trained/elite athletes
- healthy subjects without any disease or injury when testings were carried out
- no reviews or meta-analysis

2.1.2 Information Source and Search Strategy

To carry out the review, the computer database PubMed, Web of Science, Sportdiscus and Scopus were searched up until May 2020. The keywords used as search strings were "3 min all out test" OR "single all out test" AND "critical power" OR "critical speed" OR "critical velocity", originally typed in like this: ((3 min all out test) OR (single all out test)) AND ((critical power) or (critical speed) OR critical velocity)).

2.1.3 Statistical Analyses

Statistical analyses were done using the Review Manager (RevMan) computer program (version 5.3. Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). All study observations were weighted by the inverse of the reported sampling variance. Separate analyses were performed for EP/CP and WEP/*W'*, with a subdivision for the different exercise forms (cycling, running, swimming, rowing and cross-country skiing).

Using a continuous measure, variances were calculated as the standardized mean differences (SMD) between the outcome parameters from the 3MT and traditional protocols using Hedges *g* statistic under the fixed effects model (Hedges & Olkin, 2014). Effect sizes (ES) were based on Cohen's definition of *small* (≤ 0.2), *moderate* (~0.5), and *large* (≥ 0.8).

Data are presented as SMD for the performance outcomes with 95% confidence intervals (CI) and are shown in forest plots. The SMD was considered statistically significant ($p < 0.05$) if the value of 0 was not within the 95% CI. The size of each study's marker is relative to the study weight, and the pooled effects are represented using a diamond in which the location represents the ES and the width reflects the precision of the estimate.

2.1.4 Study Selection

A total of 558 studies were evaluated based on the keywords searched. An additional 5 studies were then identified as potentially eligible for inclusion, leaving a total of 563 studies screened for inclusion. Of the studies reviewed, 45 were determined to be potentially relevant based on the abstracts. Methods and partially the full texts of these articles were then screened, in which 18 were identified for inclusion. 18 of them are included in the meta-analysis. The flow diagram of the study selection in accordance to Liberati et al. (2009) can be seen in Fig. 8.

2.2 Results

2.2.1 Prisma Flow chart

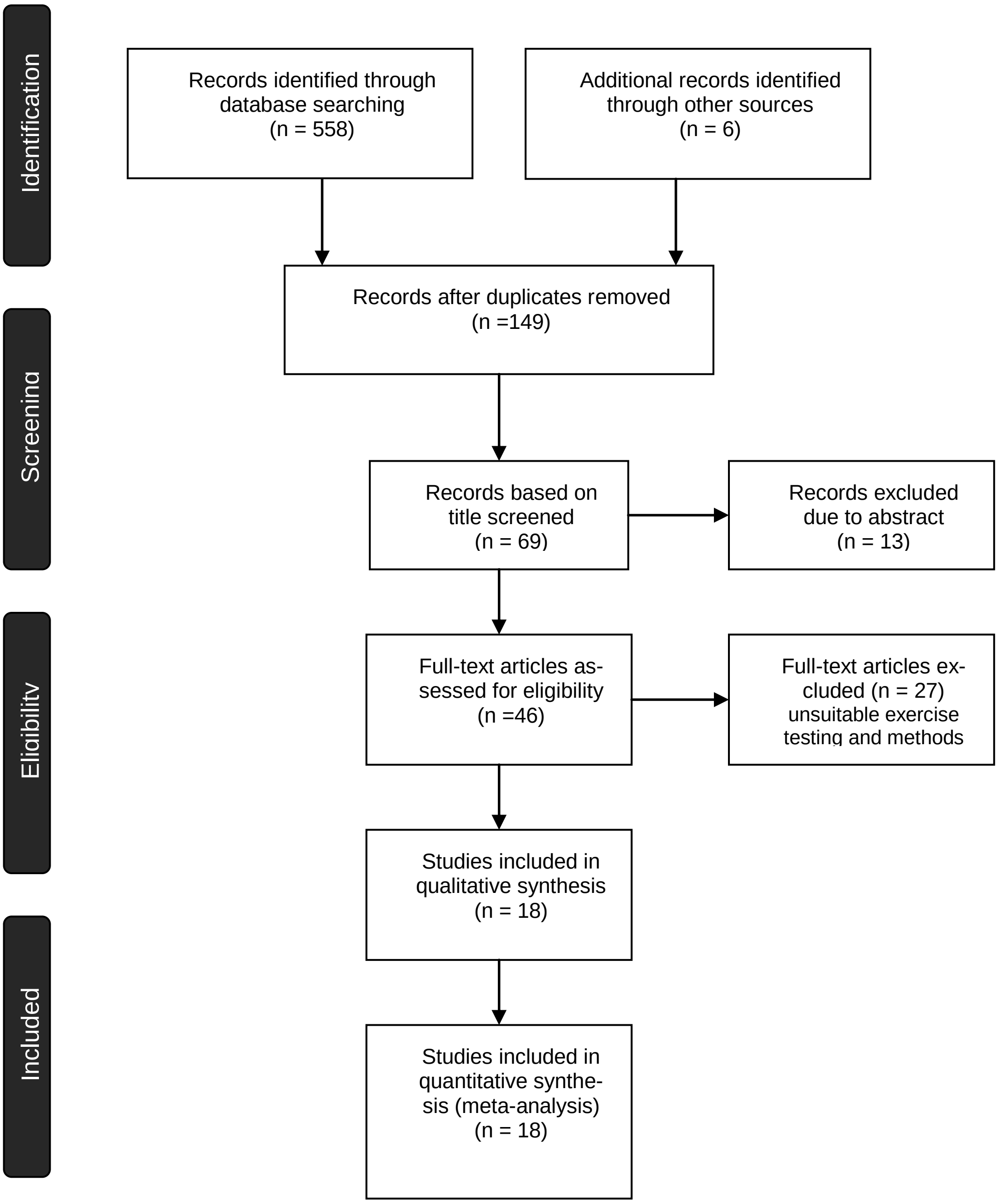


Fig. 8: Flow diagram of study selection.

2.2.2 Data Collection

Studies were sorted in a spreadsheet by exercise form and publication date. Each study was individually coded for the following variables: subject's characteristics by group including fitness level, number of participants and sex, exercise form and testing procedure, main outcomes for qualitative and trial results for quantitative analysis. For the comparison of the trial results only the relevant values have been picked out. If the study used more than one model to compare the parameters derived from the 3MT to the traditional the one result was chosen with the model that resulted in the lowest SEE, as recommended by Muniz-Pumares et al. (2019). If one study included more than one relevant outcome the result was coded as separate result, signed with (a) and (b). Table 1 summarizes all studies analyzed.

Table 1. Summary of studies meeting inclusion criteria.

Reference	Subjects: Fitnesslevel, *n* (sex)	Exercise Form and Testing Procedure	Comparison for Validation	Main Outcome	Trial Results (mean ± SD)
Vanhatalo et al. (2007)	habitually active, $n = 10$ (men)	CYCLING (electronically braked cycle ergometer) (1) GXT (2) 3MT against fixed resistance (linear factor) (3) five CWR	CP and *W'* derived from five CWR (2-15 min) using work–time and 1/time models	CP and EP were not significantly different but significantly correlated ($p = 0.37$, $r = 0.99$), SEE of CP using EP was approximately 6 W; *W'* and WEP were not significantly different but significantly correlated ($p = 0.35$; $r = 0.84$)	EP = 287 ± 55 W CP = 287 ± 56 W WEP = 15.0 ± 4.7 kJ *W'* = 16.0 ± 3.8 kJ
Vanhatalo et al. (2008a)	habitually active, $n = 9$ (7 men, 2 women)	CYCLING (electronically braked cycle ergometer) (1) GXT (2) 3MT (3) three predicting trials (a) after a 4 weeks of HIIT intervention subjects repeated the procedures (b)	CP and *W'* from three CWR (~3-9 min) using work–time and the 1/time models	EP and CP estimates before and after training were not significantly different ($p = 0.34$ pretraining; $p = 0.24$ posttraining) but significantly correlated (pretraining: $r = 0.96$, $p < 0.001$; posttraining $r = 0.95$, $p = 0.001$) Similarly, the WEP was not significantly different from the *W'* ($p = 0.58$ pretraining; $p = 0.13$ posttraining), but the two parameters significantly correlated before training ($r = 0.82$, $p = 0.007$) but not after training ($r = 0.63$, $p = 0.07$)	EP_{pre} = 225 ± 52 W CP_{pre} = 230 ± 53 W WEP_{pre} = 16.7 ± 3.5 kJ W'_{pre} = 17.2 ± 4.2 kJ (a) EP_{post} = 248 ± 46 W CP_{post} = 255 ± 50 W WEP_{post} = 17.3 ± 3.3 kJ W'_{post} = 15.5 ± 3.8 kJ (b)
Bergstrom et al. (2012)	moderately trained, $n = 12$ (6 men, 6 women)	CYCLING; the first three tests using an electronically braked cycle ergometer: (1) GXT (2) four TTE trials (3) the original 3MT (a) and (4) a 3MT with the resistance based on 4.5% of the subject's body weight by using the Monark cycle ergometer (b)	CP and *W'* estimated from four TTE trials using Wlim and Tlim	The results indicate that CP and *W'* could be estimated from a single 3MT set at 4.5% of the body weight; no significant differences ($p > 0.05$) among mean CP values and $EP_{4.5\%;}$ mean EP of 3MT was significantly greater than CP; no significant differences in *W'* for the WEP and $WEP_{4.5\%}$	EP = 193 ± 54 W CP = 178 ± 47 W WEP = 10.9 ± 2.9 kJ *W'* = 13.4 ± 6.2 kJ (a) $EP_{4.5\%}$ = 186 ± 44 W $WEP_{4.5\%}$ = 9.8 ± 4.4 kJ (b)

Barker et al. (2012)	active, *n* = 9 (3 male, 6 female 14-15 year olds)	CYCLING (1) GXT (2) up to four CWR to determine CP (3+4) CWR 10% above and 10% below CP and (5) a 3MT	CP and *W'* determined from three-four CWR using linear time-1 model	No significant differences for CP/EP (p = 0.98) and *W'*/WEP (p = 0.19) SEE for establishing CP using EP were 25 W (19.6% CV) therefore the estimation of CP using the 3MT test may be of limited value on an individual level	EP = 146 ± 30 W CP = 146 ± 27 W WEP = 10.6 ± 2.2 kJ *W'* = 12.1 ± 2.8 kJ
Dekerle et al. (2014)	active, *n* = 9 (men)	CYCLING (electronically braked cycle ergometer) (1) GXT (2) four-five CWR to determine CP and W' (3) 3MT, each participant performed (2) and (3) twice: once at 60 (a) and once 100 rpm (b)	CP and *W'* from CWR (3-15 min) using linear time-1 model	No significant difference but a significant correlation was found between EP and CP in 60 rpm ($p > 0.05$; $r = 0.85$, $p < 0.01$) and 100 rpm ($p > 0.05$; $r = 0.86$, $p < 0.01$) The Bias ± 95% limits of agreement were 14 ± 42 W at 60 rpm and 15 ± 57 W at 100 rpm. WEP was not significantly different to *W'* ($p > 0.05$) but with a significant correlation at 60 rpm ($r = -0.71$, $p < 0.05$).	EP_{60rpm} = 259 ± 40 W CP_{60rpm} = 245 ± 38 W WEP_{60rpm} = 14.7 ± 3.0 kJ W'_{60rpm} = 16.2 ± 3.2 kJ (a) EP_{100rpm} = 227 ± 57 W CP_{100rpm} = 212 ± 44 W WEP_{100rpm} = 17.3 ± 3.1 kJ W'_{100rpm} = 20.6 ± 6.4 kJ (b)
Karsten et al. (2014)	cyclists, *n* = 13 (12 men, 1 woman)	CYCLING (electronically braked cycle ergometer) (1) incremental test and familarization 3MT (2) 3 CWR (3) 3MT	CP and W' from CWR using work-time and 1/time models	CP and EP ($p < 0.001$) and *W'* and WEP ($p < 0.001$) were significantly different. The study suggests that using an isokinetic mode 3MT, while yielding a reliable measure of EP, does not provide a valid measure of CP.	EP = 290 ± 41 W CP = 259 ± 38 W WEP = 12.5 ± 4.3 kJ *W′* = 16.6 ± 4.8 kJ
Dicks et al. (2016)	triathletes, cyclists and recreationally trained individuals, *n* = 12 (9 men, 3 women)	CYCLING (electronically braked cycle ergometer) (1) GXT (2-3) two 3MTs: one in % of body weight and one using the original linear-factor protocol (4-6) 3 exhaustive square-wave bouts	CP and *W'* from 3 exhaustive square-wave bouts via linear regression of work–time and power–inverse-time models	Estimates of CP derived from the $3MT_{\%BM}$, $3MT_{rpm^2}$, work–time, and 1/time models did not significantly differ (p = 0.72) Similarly, estimates of *W′* between all methods did not significantly differ (p = 0.07) The $3MT_{\%BM}$ is a valid, single-visit protocol for determining CP and *W′*.	$EP_{\%BM}$ = 235 ± 56 W $CP_{work–time}$ = 231 ± 57 W $WEP_{\%BM}$ = 7.88 ± 2.91 kJ $W'_{work–time}$ = 9.20 ± 3.84 kJ (a) EP_{rpm^2} = 234 ± 62 W WEP_{rpm^2} = 6.97 ± 3.11 kJ (b)

Clark et al. (2016)	competitive cyclists, *n* = 10 (7 men, 3 women)	CYCLING (own road bicycles fastened on a CompuTrainer) (1) 3MT (2-4) three different exhaustive bouts with preferred cadence	CP and *W'* from 3 constant load bouts (3, 6, 9 min) using linear work-time and power-inverse time models	Results for CP & *W'* from the 3MT, the W-t model and the 1/t model did not significantly differ (p = 0.11) Similarly, the results for WEP, the W-t model and the 1/s model did not significantly differ (p = 0.15) The use of the 3MT and the CP concept on the CompuTrainer is a valid procedure.	EP = 215 ± 40 W $CP_{W\text{-}t}$ = 212 ± 36 W WEP = 11.2 ± 4.0 kJ $W'_{W\text{-}t}$ = 12.1 ± 6.5 kJ
Mattioni et al. (2016)	recreational and competitive cyclists, *n* = 13 (9 men, 4 women)	CYCLING (electronically braked cycle ergometer) (1) GXT (2) five constant power output trials to exhaustion (1-20 min) (3) 3MT with linear factor (4) CWR for determination of MLSS	5 TTE trials by fitting the two-parameter nonlinear model	There were no significant differences (p > 0.05) between the PO values obtained from EP and CP, limits of agreement (LOA) from Bland-Altman plots between CP and EP (-39 to 31W) were wide. WEP presented consistent lower values than *W'* and were significantly different (p < 0.05)	EP = 250 ± 51 W CP = 253 ± 44 W WEP = 7.2 ± 5.5 kJ *W'* = 20.3 ± 5.9 kJ
Bartram et al. (2017)	elite cyclists, *n* = 6 (men)	CYCLING (own road bicycles rear mounted to Lemond Revolution trainer) (1) six self-paced efforts to exhaustion (1, 4, 6, 8 and 10 min) and (2) the 3MT	Traditional work versus time calculations of CP and *W'* using the five self-paced efforts	CP estimated from the 3MT was significantly higher than from the traditional approach (p < 0.001), whilst *W'* was significantly lower (p = 0.02) so that in elite cyclists the 3MT may not be suitable to estimate CP when compared to the traditional method	EP = 402 ± 33 W CP = 351 ± 27 W WEP = 15.5 ± 3.0 kJ *W'* = 24.3 ± 4.0 kJ
Wright et al. (2017)	cyclists, *n* = 12 (men)	CYCLING (1) GXT (2-4) three fixed power tests to calculate CP and W' (5-8) four 3MTs: 2 isokinetic (constant cadence) and 2 linear tests (fixed resistance)	3 CWR calculating CP and *W′* using the 1/time model	No significant difference between CP and EP-isokinetic (p = 0.377). Significant differences between EP_{linear} and CP (p = 0.004), WEP-isokinetic and *W′* (p < 0.001) and WEP_{linear} and *W′* (p < 0.001). The 3MT isokinetic test provides a valid estimate of CP and a reliable estimate of EP. The linear test provides a reliable estimate of EP, but not a valid estimate of CP. The results suggest that the 3MT should not be used to estimate *W′*.	$EP_{isokinetic}$ = 240.9 ± 23.3 W CP = 244.9 ± 26.2 W (a) $WEP_{isokinetic}$ = 15.6 ± 5.6 kJ *W'* = 22.7 ± 5.6 kJ EP_{linear} = 275.1 ± 41.2 W WEP_{linear} = 13.5 ± 4.7 kJ (b)

Wright et al. (2019)	trained cyclists, $n = 10$ (men)	CYCLING (electronically braked cycle ergometer) (1) GXT for calculation of GET, maximal aerobic power (MAP) and $\dot{V}O_{2max}$ (2) three separate TTE (3) 3MTs using different cadences	Three TTE at 80, 100 and 105% MAP, CP and W' were calculated using linear regression from the power-1/time	The 3MT is sensitive to changes in cadence, EP is reduced when cycling at higher than preferred cadences, providing better estimates of CP. Significant differences were found between CP and $EP_{preferred}$ ($p < 0.001$). No significant differences were seen between CP and EP_{+10} ($p = 0.331$). Significant differences were seen between *W′* and WEP at all tested fixed resistances.	$EP_{preferred}$ = 296.6 ± 26.1 W CP = 267.5 ± 22.6 W $WEP_{preferred}$ = 11.2 ± 4.5 kJ *W'* = 20.5 ± 5.1 kJ (a) EP_{+10} = 278.1 ± 30.9 W WEP_{+10} = 10.9 ± 4.8 kJ (b)
Broxterman et al. (2013)	not active to highly trained, $n = 7$ (4 men, 3 women)	RUNNING (treadmill and track) (1) GXT (2) traditional determination of the speed-time relationship: three constant speed runs to exhaustion on a treadmill (3) validation of CS by running 1) slightly above and 2) slightly below CS (3) two 3MT on a track, one as familiarization	three constant speed runs to exhaustion (2-10 min), CS and *D'* were determined by fitting it to the two-parameter linear speed-1/time model4	ES was not significantly different from CS. While DES was not significantly different from *D*', it underestimated *D'* in 5 of 7 subjects. Thus, CS can be accurately determined using a single 3MT, while caution should be used when relating DES to *D*'.	ES = 13.4 ± 2.8 km/h CS = 13.3 ± 2.8 km/h DES = 141 ± 34 m *D'* = 204 ± 103 m
Gama et al. (2018)	physically active, $n = 8$ (men)	RUNNING (tethered running on non-motorized treadmill) (1) tethered running familiarization consisting of sprints (2) CP sessions: four efforts until exhaustion against resistances (3) 3MT	CP and *W'* parameters originating from the Hyp model, the vs t model and the P vs 1/t model	EP value was similar and not significantly different ($p = 0.486$) to CP derived from all three models, WEP was not similar and significantly different ($p < 0.001$) to *W'* from conventional models. Positive results ($r = 0.78$–0.98 and ICC = 0.88–0.99) of Pearson correlation and intraclass correlation were found for CP and EP. *W'* from the three models was not significantly correlated with WEP ($r = 0.37$–0.52). 3MT in tethered running on non-motorized treadmills is a valid test for estimating CP in a single day of application but not of *W'*	EP = 181.7 ± 52 W CP = 178.2 ± 61 W WEP = 17.9 ± 4.8 kJ *W'* = 50.2 ± 15.3 kJ

Tsai and Thomas (2017)	average trained swimmers and triathletes, $n = 10$ (4 men, 6 women)	SWIMMING (1) 3MT (2) 4 set distance time trials to determine CS and *D'*	CS and *D'* determined from 3 traditional models: linear distance-time: LIN, linear speed-time-1: INV, nonlinear time-speed: NLIN	No significant difference between the ES and CS derived from traditional models except for the INV model (INV $p = 0.0311$). Correlations between CS and ES were significant ($r = 0.95$, $p < 0.01$). However, *D'* differed and post hoc analysis indicated that *D'* estimated from 3MT was significantly lower than LIN ($p = 0.0052$) and NLIN ($p < 0.001$). Correlations were not significant ($r < 0.55$, $p > 0.1$). The study suggests the 3MT as a valid protocol for estimating aerobic capacity (CS) in swimming. Further investigation should focus on *D'*.	ES = 0.91 ± 0.13 m/s CS = 0.91 ± 0.14 m/s DES = 17.51 ± 7.54 m *D'* = 34.37 ± 13.66 m
Piatrikova et al. (2018)	highly trained swimmers, $n = 13$ (6 male, 7 female 14-18 years)	SWIMMING (1) 3MTs, one for familiarization and two to test reliability (2) four TT	200, 400, 600 and 800 m TT, linear regression was used to calculate CS and *D′* using the distance-time (DT) and speed-1/time model (1/T)	CS from 3MT did not significantly differ from the conventional protocols and significantly correlated ($r = 0.95$, $p < 0.001$). DES was lower compared to D'_{DT} ($p < 0.05$) and $D'_{1/T}$ (p = 0.09). Correlations between DES and D' were significant ($r = 0.79$, $p = 0.002$). 3MT is a valid protocol for the estimation of CS and produces high test-retest reliability for CS and *D′* in highly-trained swimmers	ES = 1.33 ± 0.06 m/s CS = 1.33 ± 0.06 m/s DES = 19.50 ± 3.52 m *D′* = 22.15 ± 5.75 m
Fukuda et al. (2014)	recreationally active, $n = 14$ (men)	CROSS-COUNTRY SKI (using an upper-body ergometer) (1) GXT to determine $\dot{V}O_{2max}$ (2) two 3MTs (3) three TT to estimate CP and *W'*	Distances of 300, 650 and 1000 m and linear regression was used to determine CP and *W'*	EP and CP were not significantly different between the testing methodologies ($p = 0.290$) but were significantly correlated ($r = 0.780$). No significant difference in WEP and *W′* ($p = 0.947$) and no significant relation ($r = 0.119$) The 3MT using ski ergometry was shown to produce concurrently valid results with the traditional CP test for CP but not *W′* and elicited similar maximal oxygen uptake values when compared to a GXT.	EP = 148 ± 33 W CP = 157 ± 49 W WEP = 8.4 ± 3.0 kJ *W'* = 8.3 ± 3.0 kJ

Cheng et al. (2012)	experienced rowers, *n* = 18 (men)	ROWING (rowing ergometer) (1) GXT (2) three CWR to establish CP and *W'* (3) two 3MT against a fixed resistance	CP and *W'* using the work-time and the power-time models	EP and WEP determinations have moderate reproducibility (p = 0.002) and EP is able to appropriately estimate aerobic capacity. EP was significantly correlated with CP (p < 0.001), with no significant differences observed between the EP and CP values (p = 0.474). However, WEP did not significantly correlate with *W'* (p = 0.254), and was significantly higher than the *W'* values.	EP = 269 ± 39 W CP = 276 ± 32 W WEP = 16.63 ± 4.03 kJ *W'* = 12.33 ± 3.23 kJ

GXT = graded exercise test; TTE = time to exhaustion; TT = time trial; CWR = constant work rate; $\dot{V}O_{2max}$ = maximum oxygen uptake; MLSS = maximal lactate steady state; 3MT = 3-min all-out test; EP = end-test power; ES = end-test speed; WEP = work above end-test power; DES = distance above end-test speed. (a) and (b) when more than one result was relevant for meta-analysis.

2.3 Results of meta-analysis

The analysis on both parameters of the P-D relationship compromised a number of 259 subjects and 24 ESs, nested within 18 studies. There was no significant difference and a small effect size between 3MT and traditional CP values (ES = 0.16; 95% CI: -0.01 to 0.33; *p* = 0.07) (Fig. 9).

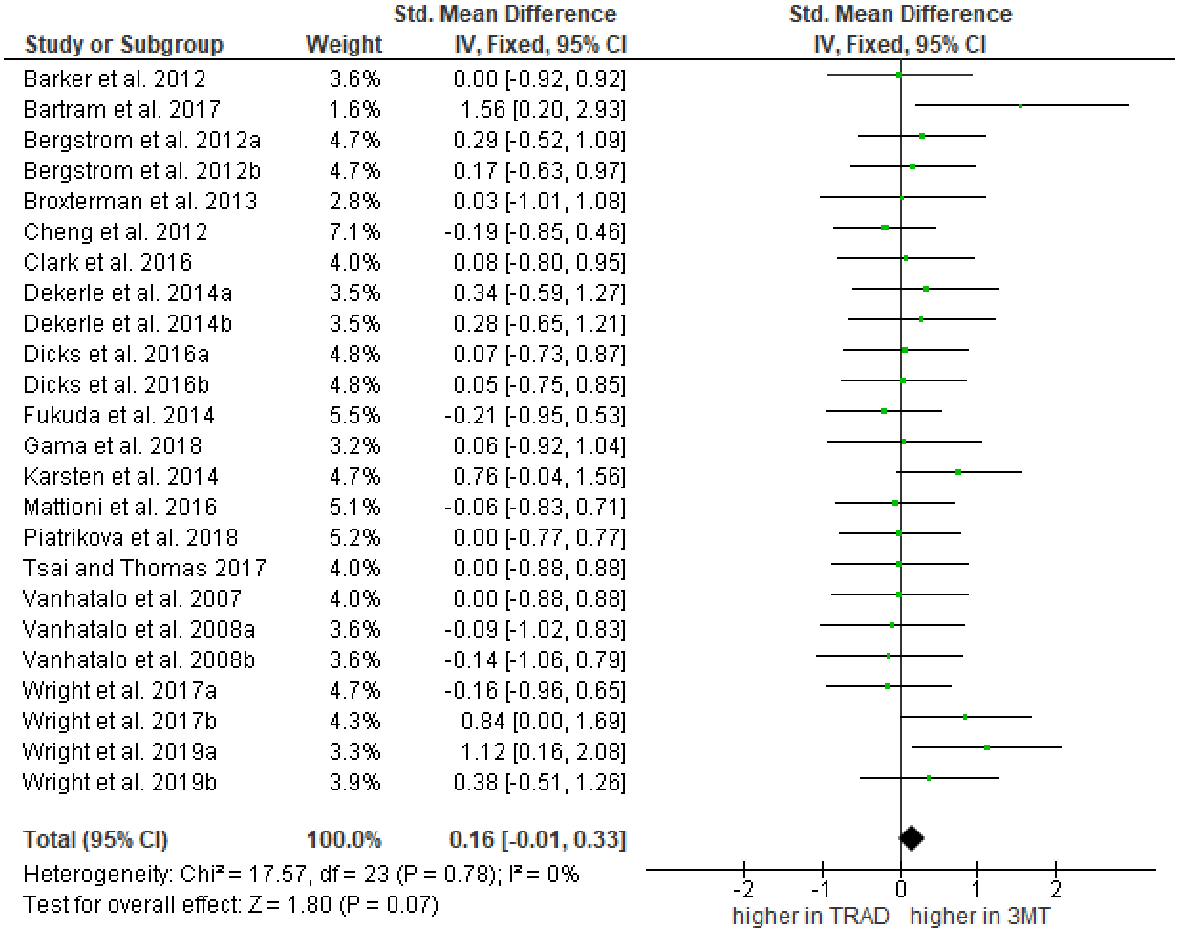


Fig. 9: Forest plot of the difference in CP between 3MT and traditional (TRAD) protocols.

The analysis on WEP and *W'* revealed a significant difference (lower values) and a moderate effect size when comparing 3MT and traditional protocols (ES = 0.62; 95% CI: 0.81 to 0.44; *p* < 0.001) (Fig. 10).

Study or Subgroup	Weight	Std. Mean Difference IV, Fixed, 95% CI
Barker et al. 2012	3.9%	-0.57 [-1.51, 0.38]
Bartram et al. 2017	1.4%	-2.30 [-3.89, -0.70]
Bergstrom et al. 2012a	5.2%	-0.50 [-1.31, 0.32]
Bergstrom et al. 2012b	5.1%	-0.65 [-1.47, 0.18]
Broxterman et al. 2013	2.9%	-0.77 [-1.87, 0.33]
Cheng et al. 2012	6.8%	1.15 [0.44, 1.86]
Clark et al. 2016	4.5%	-0.16 [-1.04, 0.72]
Dekerle et al. 2014a	3.9%	-0.46 [-1.40, 0.48]
Dekerle et al. 2014b	3.8%	-0.63 [-1.58, 0.33]
Dicks et al. 2016a	5.3%	-0.37 [-1.18, 0.43]
Dicks et al. 2016b	5.1%	-0.62 [-1.44, 0.21]
Fukuda et al. 2014	6.3%	0.03 [-0.71, 0.77]
Gama et al. 2018	1.6%	-2.69 [-4.15, -1.24]
Karsten et al. 2014	5.3%	-0.87 [-1.68, -0.06]
Mattioni et al. 2016	3.4%	-2.22 [-3.24, -1.21]
Piatrikova et al. 2018	5.6%	-0.54 [-1.32, 0.25]
Tsai and Thomas 2017	3.4%	-1.46 [-2.48, -0.45]
Vanhatalo et al. 2007	4.5%	-0.22 [-1.10, 0.66]
Vanhatalo et al. 2008a	4.0%	-0.12 [-1.05, 0.80]
Vanhatalo et al. 2008b	3.9%	0.48 [-0.46, 1.42]
Wright et al. 2017a	4.4%	-1.22 [-2.11, -0.34]
Wright et al. 2017b	3.8%	-1.72 [-2.68, -0.76]
Wright et al. 2019a	2.9%	-1.85 [-2.94, -0.77]
Wright et al. 2019b	2.9%	-1.86 [-2.94, -0.77]
Total (95% CI)	**100.0%**	**-0.62 [-0.81, -0.44]**

Heterogeneity: Chi² = 77.18, df = 23 (P < 0.00001); I² = 70%
Test for overall effect: Z = 6.56 (P < 0.00001)

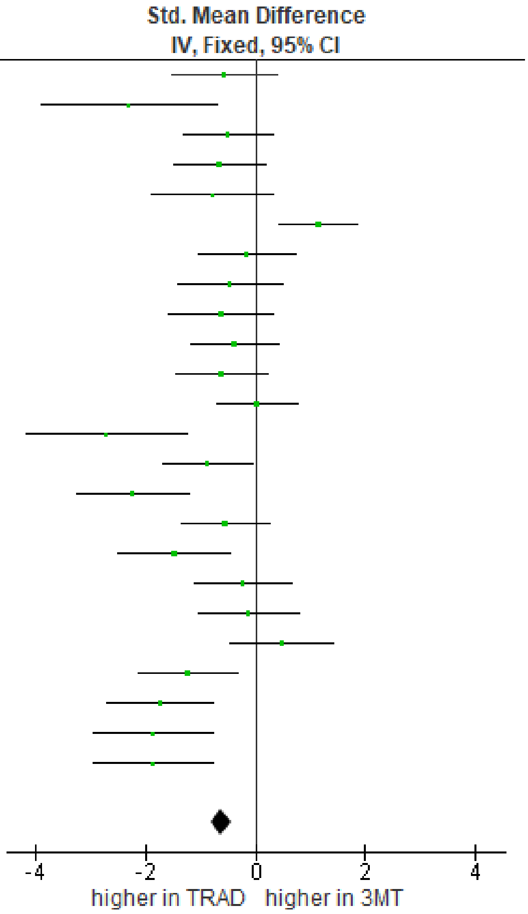


Fig. 10: Forest plot of the difference in *W'* between 3MT and traditional (TRAD) protocols.

2.3.1 Results for each Exercise Form

2.3.1.1 Cycling

The analysis on the validity of the 3MT in cycling compromised 189 subjects and 18 ESs, nested within 12 studies. There was a significant difference (higher values) and a moderate effect size between 3MT and traditional CP values (ES = 0.25; 95% CI: 0.05 to 0.46; p = 0.02) (Fig. 11).

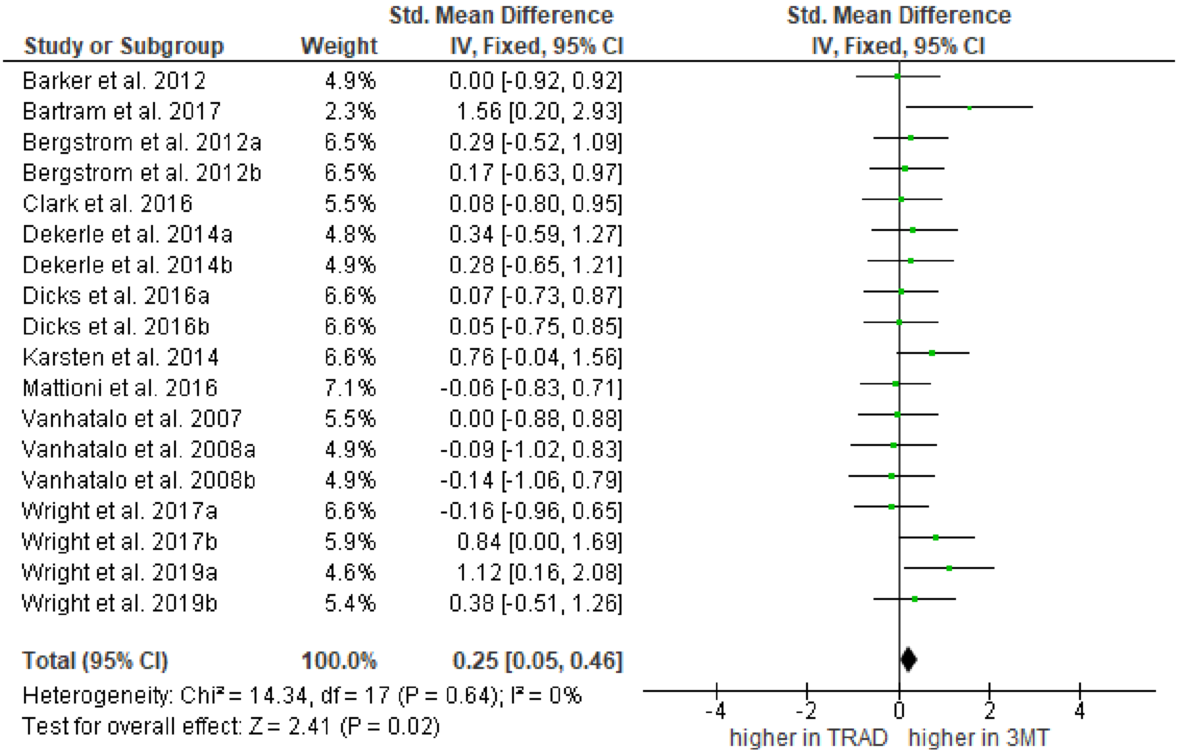


Fig. 11: Forest plot of the difference in CP between 3MT and traditional (TRAD) protocols in cycling.

The analysis on WEP and *W'* in cycling revealed a significant difference and moderate effect size when comparing values derived from 3MT and traditional protocols (ES = 0.76; 95% CI: 0.98 to 0.54; $p < 0.001$) (Fig. 12).

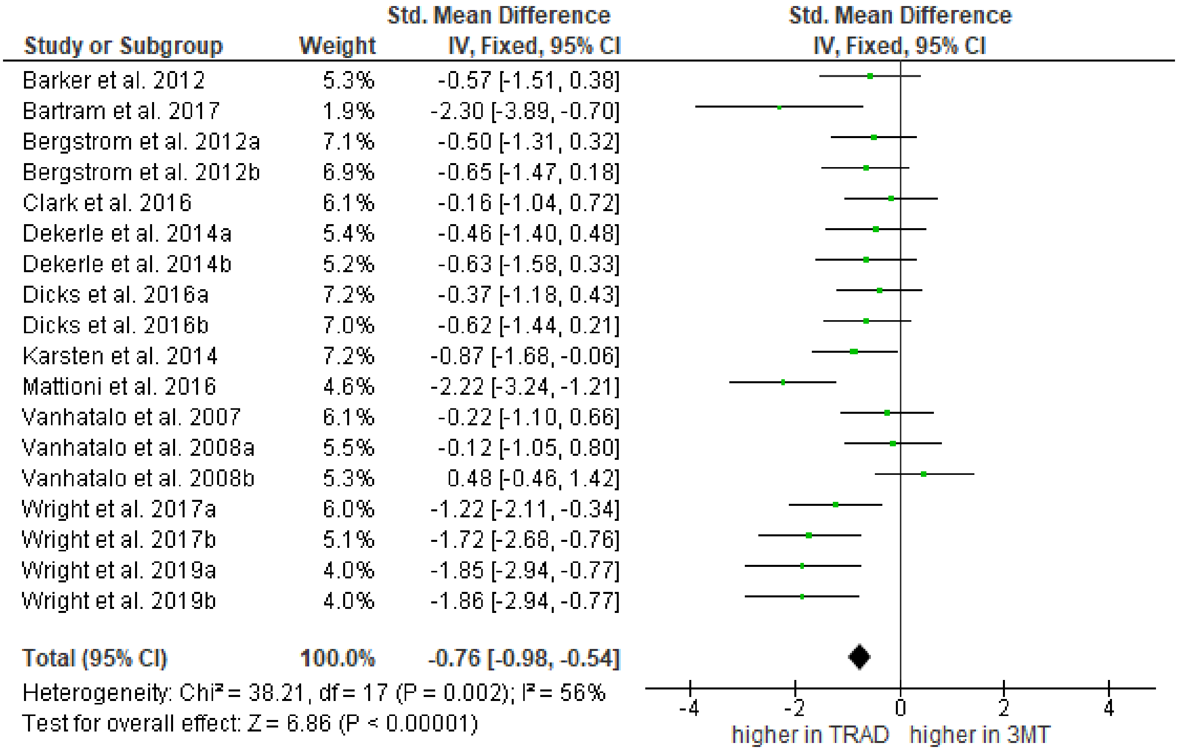


Fig. 12: Forest plot of the difference in *W'* between 3MT and traditional (TRAD) protocols in cycling.

2.3.1.2 Running

The analysis on the validity of the 3MT in running compromised 15 subjects and 2 ESs, nested within 2 studies. There was no significant difference and a trivial effect size between 3MT and traditional CP values (ES = 0.05; 95% CI: -0.67 to 0.76; p = 0.90) (Fig. 13).

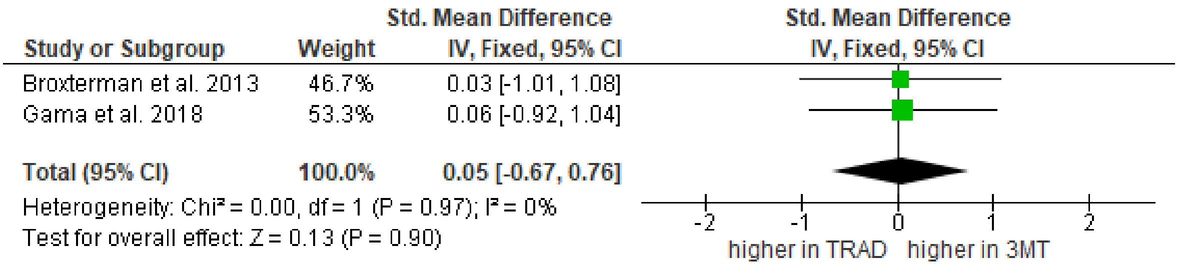


Fig. 13: Forest plot of the difference in CP between 3MT and traditional (TRAD) protocols in running.

The analysis on WEP and *W'* in running revealed a significant difference and a large effect size when comparing values derived from 3MT and traditional protocols (ES = 1.47; 95% CI: 2.35 to 0.59; p = 0.001) (Fig. 14).

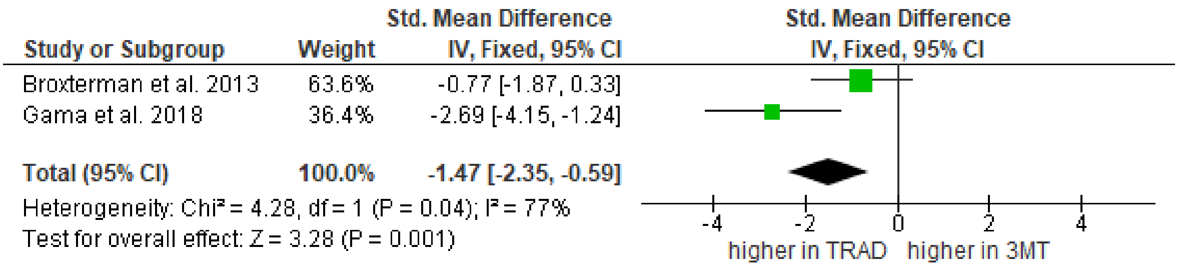


Fig. 14: Forest plot of the difference in *W'* between 3MT and traditional (TRAD) protocols in running.

2.3.1.3 Swimming

The analysis on the validity of the 3MT in swimming compromised 23 subjects and 2 ESs, nested within 2 studies. There was no significant difference and a trivial effect size between 3MT and traditional CP values (ES = 0.00; 95% CI: -0.58 to 0.58; p = 1.000) (Fig. 15).

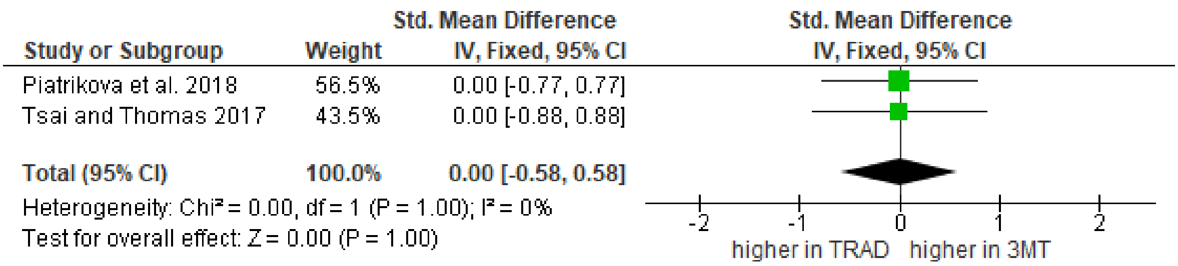


Fig. 15: Forest plot of the difference in CP between 3MT and traditional (TRAD) protocols in swimming.

The analysis on WEP and *W'* in swimming revealed a significant difference and a large effect size when comparing values derived from 3MT and traditional protocols (ES = 0.89; 95% CI: 1.51 to 0.27; p = 0.005) (Fig. 16).

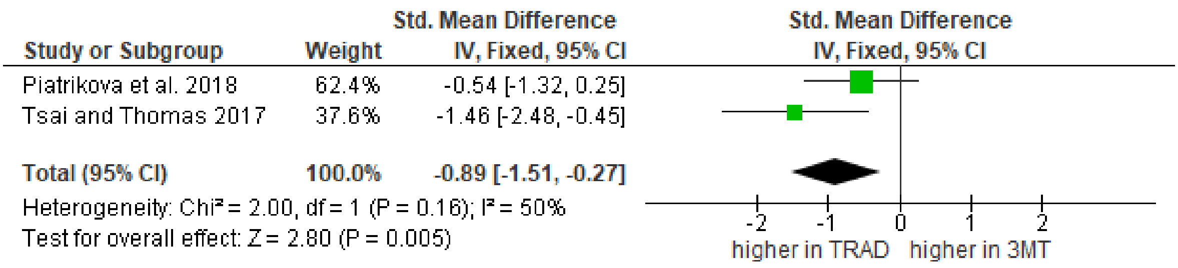


Fig. 16: Forest plot of the difference in *W'* between 3MT and traditional (TRAD) protocols in swimming.

2.3.1.4 Cross-Country Skiing

Only one study met the eligibility criteria for cross-country skiing exercise. Fukuda et al. (2014) tested 14 recreationally active males who were unaccustomed to ski ergometry. The derived EP and CP values from the 3MT and the conventional protocol on a ski-ergometer were not significantly different (p = 0.290) and highly correlated (r = 0.780). WEP and *W'* were similar (p = 0.947) but not related (r = 0.119). The authors suggest that the 3MT using ski-ergometry produces concurrently valid results with the traditional CP test for the aerobic parameter of the P-D relationship, but not the anaerobic parameter *W'*, and elicited similar maximal oxygen uptake values when compared to a GXT.

2.3.1.5 Rowing

Only one study met the eligibility criteria for rowing exercise. Cheng et al. (2012) tested 18 experienced rowers on a rowing ergometer and found out that EP is able to appropriately estimate aerobic capacity when comparing it to traditional CP. There were no significant differences observed between the EP and CP values (p = 0.474) and EP was significantly correlated with CP ($p < 0.001$). However, WEP did not significantly correlate with *W'* (p = 0.254), and was significantly higher than the *W'* values.

2.4 Discussion

2.4.1 Qualitative Summary of Evidence

The primary purpose of this part of the thesis was to systematically review the current literature and evaluate the overall difference between the parameters estimates of the P-D relationship derived from a 3MT and traditional protocols by a meta-analysis. The pooled analysis for the difference between these two determinations showed no statistically significant difference in CP/EP (small ES) and a significant difference (moderate ES) in *W'*/WEP.

In most of the cases, WEP or DES has shown to be significantly lower than the traditional determined *W'* or *D'*. Interestingly, whilst the 3MT seems to underestimate *W'* or *D'*, there is a moderate but non-significant (except in cycling) tendency for CP to be over predicted. This over-prediction may be traced back to the fact that no true all-out effort happened in the onset of the 3MT, what also explains the lowered WEP values.

Moreover, there seems to be an inverse relationship of CP and *W'*: When CP gets higher, *W'* is lowered. This is in accordance with previous findings of Vanhatalo et al. (2008a; 2010) and Burnley and Jones (2007). They showed a tendency for *W'* to be reduced after interventions such as training and hyperoxia, which are both effective in altering CP and also $\dot{V}O_{2max}$ (Vanhatalo et al., 2008a).

2.4.1.1 Cycling

Apparent from the collected data, the most investigated form of exercise is cycling. Based on the original 3MT of Vanhatalo et al. (2007) which requires two laboratory visits, a lot of other research groups focused on different testing formats. For example, Bergstrom et al. (2012) showed that a modified 3MT with a resistance set at 4.5% of the body weight could be used for a valid estimation of CP and *W'*. Similarly, Dicks et al. (2016) calculated the load based on age, sex, body mass and self-reported physical activity levels and found no differences in alternative testing protocols and the original 3MT for both parameter estimates. Furthermore, authors validated the procedures by finding no significant differences between both of the P-D parameters derived from the 3MT and those from 3 CWR bouts using linear models. Moreover, Clark et al. (2016) validated the determination of CP and *W'* using the CompuTrainer, an ergometer often used for training by cyclists. Their results indicated good agreements between traditional ways to determine CP and the new approach for EP. However, the CV seems to be higher in WEP (~25%) than that of EP (~4%) (Clark et al., 2016; Dicks et al., 2016).

Karsten et al. (2014) showed that using an isokinetic mode 3MT does not provide valid measures of both, CP and *W'*. Specifically, the mean PO over the final 30 s of the test appeared to be significantly higher when compared to conventional CP values. Additionally, *W'* seems to be underestimated. The authors state that the discrepancy to the studies mentioned before may be due to several methodological differences. For example, in contrast to Vanhatalo et al. (2007), the study of Karsten et al. (2014) was conducted on a relatively homogenous sample of trained cyclists and moreover they used different ergometers and a different method for the 3MT (isokinetic approach vs. 'linear factor').

Wright et al. (2017) captured the discrepancy between the different ergometers and showed that a 3MT in an isokinetic mode (with a predefined cadence) provided valid estimates of CP, while the linear mode on the contrary (with a fixed resistance) did not provide a valid estimation in this study, which is in vast contrast to the pioneer work of Vanhatalo et al (2007). Wright et al. (2017) suggest that care should be taken when selecting the testing mode for a 3MT cycling test. Although the linear mode has been successfully implemented into research (Vanhatalo et al., 2007), results of Wright et al. (2017) highlighted the causes for concern: The duration of testings, the testing ergometer, its mode and cadence selection (Vanhatalo et al., 2008b) may all affect the estimation of the parameters of the P-D relationship.

Consistent with most of the studies included in the analysis, neither of the testing methods that were used in the study of Wright et al. (2017) provided valid estimates of *W'*. In a follow-up Wright et al. (2019) showed that a higher cadence (10 rev/min above preferred cadence) provided a better estimation of CP in the linear mode than with a preferred cadence, highlighting the importance of selecting the right cadence prior to performing a 3MT. Again, *W'* was significantly underestimated, no matter at which cadence testing was carried out. Wright et al. (2019) explained the lower power output of the 3MT with the higher selected cadence (that caused better "real CP" estimates) as follows:

A higher cadence leads into a fastened muscular fatigue. In terms of the physiological basis of the 3MT it is essential that the finite work capacity is exhausted within the first 150 s of the test. Therefore, a faster eventuating fatigue is likely to result into a lower EP, which potentially provides a more accurate estimation of CP. Alternative procedures warrant caution when talking about the validation of EP and WEP but can also be a useful tool to determine CP and *W'* (Wright et al., 2019).

Also noticeable is the study of Barker et al. (2012) as this was the first study to validate EP in young people (14-15 year olds). CP is said to be the critical threshold for power outputs which end up in steady-state oxygen uptake and blood lactate response (heavy exercise) and those where a steady-state cannot be held any longer (severe exercise) (Barker et al., 2012). However, authors showed up that this may not be the fact in young people. In some instances adolescents failed to attain $\dot{V}O_{2max}$ and experienced a fall in oxygen uptake during severe exercise. This underlines the assumption that they might have a reduced anaerobic fitness. There were no significant differences between the traditional and the 3MT parameters of the P-D relationship, but a large variation within individuals leave the 3MT derived parameters of limited value on individual levels.

Another study that stands out is the one of Bartram et al. (2017) which is the only one that investigated the validity of the 3MT in elite athletes. The 3MT significantly overestimated CP and underestimated *W'*, leading into the assumption that it is not suitable as a replacement for the traditional estimation. Interestingly, the authors suggest that most of the studies showing an overestimation of CP involve rather well trained athletes, what was also the case when having a look at the study of Karsten et al. (2014). Moreover, the prevalence of studies showing a CP overestimation is high in all kind of subjects in studies, and the authors try to explain this as follows:

The overestimation of CP might happen when *W'* has not been fully depleted in the first 150 s and therefore is still contributing in the final 30 s of the test. This means that the athletes, consciously or subconsciously, pace although being told not to do so (Wright et al., 2019). In this connection, the authors adduce the teleoanticipation phenomena. According to Faria (1992), this term has been described as “a subconscious fatigue avoidance mechanism” by helping the athlete to constrain to a certain work rate so that a successful termination of the exercise task is guaranteed. Teleoanticipation is based on past experiences (Mauger et al., 2009). Thus, the more experience of maximal work is made the easier it will get to maximize performance over a given amount of time.

This concept may be one explanation why the derived EP and WEP parameters often do not truly represent CP and *W'*. Wright et al. (2019) additionally cause for the thought that the idea that one can maintain CP once *W'* is depleted is after all just a mathematical construct that is physiologically difficult to prove.

2.4.1.2 Running

Two studies met the eligibility criteria in terms of running and similar to the results of the cycling studies it seems as if CS can be accurately determined using a single 3MT whereas caution should be used when relating DES to *D'*. Broxterman et al. (2013) found no significant difference neither in aerobic nor in anaerobic parameters of the P-D relationship, but DES underestimated *D'* in 5 of 7 subjects. In accordance to the discrepancy between DES and *D'*, the authors suggested several plausible explanations. The constant speed runs for the determination of CP and *W'* were carried out on a treadmill, thus indoor, whereas the 3MT has been done outdoor on a track. The acceleration at the onset of the 3MT might require additional energy (*D'*) due to upcoming inertia and therefore, the DES measured may not entirely represent the actual distance that the athlete would be able to cover. Additionally these authors stated that measuring the work of running is difficult since the variability in stride mechanics and ensuing fatigue arise.

The second study that has been included was carried out on a non-motorized treadmill in tethered running so that outcomes where actually measured in power as in the cycle studies instead of speed. Gama et al. (2018) suggest that the 3MT is a valid test for estimating CP but not *W'*. These authors attribute this to the explanation of Vanhatalo et al. (2007), where the authors indicate that 180 s of testing may not be enough to deplete the anaerobic metabolism reserves. Also, Gama et al. (2018) allude to the initial acceleration phenomenon that may arise. De Aguiar et al. (2013) reported that, by measuring oxygen consumption when applying CS on a treadmill, oxidative metabolism seem to raise at fast-start strategies, leading into attenuated anaerobic energy.

2.4.1.3 Swimming

Two studies met the eligibility criteria in terms of swimming. In common with cycling and running it can be concluded in swimming that EP derived from a 3MT can accurately represent CS, but DES appears to be consistently lower than *D'*. Tsai and Thomas (2017) explained that this might be due to an exponential increase in energetic cost that swimmers encounter because of the hydrodynamic drag that arises in higher speeds, as explained in the study of Di Prampero et al. (2008). Partially, the inaccuracy in the constant distance-time protocols of the conventional method to estimate *D'* could also be the reason for the differences. It is important to note that the authors tested athletes with different fitness levels, ranging from barely to highly trained, which they state may be a limitation but also a strength of their study.

Contrary to this, Piatrikova et al. (2018) tested highly trained swimmers that were accustomed to competitive swimming. In this homogenous setting the authors came to equal results as the 3MT pioneers (whether in swimming or other exercise forms) before, suggesting the 3MT to be a valid protocol to estimate CS in highly trained athletes, but caution is warranted when it comes to *D'*. The authors indicate that *D'* seems to be a more variable measure than CS appears to be and that it is more sensitive to the testing protocol used (Coakley & Passfield, 2018; Triska et al., 2018), to nutrition (Miura et al., 2000), to prior exercise (Vanhatalo & Jones, 2009) and even mental fatigue (Salam et al., 2018). Furthermore, they also underline the drag and the resulting changes in stroke mechanics due to the exponential relationship between speed and energy expenditure and indicate that defining both parameters of the P-D relationship using the 3MT might be problematic in terms of swimming. Similar to the findings of Vanhatalo et al. (2008b), who found out that *W'* was significantly lower in high cadence trials, stroke rate in the study of Piatrikova et al. (2018) during the 3MT was higher than compared to the TT of the conventional protocol. That may affect energy expenditure and oxygen consumption (Wakayoshi et al., 1995) and cause the lowered values of DES.

2.4.1.4 Cross Country Skiing

Fukuda et al. (2014) were the first and to date the only ones who validated the P-D parameters on a cross-country ski ergometer using the 3MT in comparison to a traditional protocol. EP and CP were not significantly different between the testing methodologies and highly correlated, whereas WEP and *W'* were not significantly different but not related. Leaving out the fact that most of the studies investigating the 3MT come to the same result, the authors attribute the lack of relationship between *W'* and WEP to some outliers. They suggest that while *W'* and WEP estimations normally have the trend to highly vary, their results support the notion of their interchangeable use at least in recreationally active adults. Moreover, the testing elicited similar $\dot{V}O_{2max}$ values when compared to the GXT, so the authors suggest that this has the benefit to offer $\dot{V}O_{2max}$ estimations and only one testing session is necessary to assess the P-D relationship and $\dot{V}O_{2max}$.

2.4.1.5 Rowing

In rowing, Cheng et al. (2012) demonstrated that the 3MT is able to provide an accurate estimation of the CP in experienced rowers. The authors suggest that a 3MT can be a valid alternative for a traditional CP estimation and also for an incremental exercise test, at least to establish $\dot{V}O_{2max}$. In contrast to all other studies mentioned before, *W'* was significantly higher in 3MT compared to the conventional estimation.

The general discrepancy between *W'* and WEP may be attributable to the specific movement patterns of rowing. A rowing cycle combines a “drive phase”, which is the frontal to the rear movement reversal, and a “recovery phase”, which spans from the rear reversal to the next frontal reversal (Janshen et al., 2009). The higher WEP in the study of Cheng et al. (2012) can be explained as follows: The drive phase is demanding a high activation of upper and lower body muscles, whereas exactly the same involved muscles are relaxed during the recovery phase (2011). Therefore, the interplay of these main phases offer the muscles rest intervals which potentially slow down power output declines, producing increased WEP values. Because of the complex procedure and technique of rowing, Cheng et al. (2012) chose to test only experienced rowers to gain homogenous results, as muscle activities and force profiles may vary if the experience levels differ.

2.4.2 Discussion, Findings and Limitations

2.4.2.1 Validation of the P-D Parameters

As recommended by Muniz-Pumares et al. (2019), the validity of the determined values was reviewed by the so-called “Gold Standard” to determinate the P-D relationship. Pettitt et al. (2019) on the contrary criticize that applying the traditional model as the “Gold Standard” may be simply relying on tradition, true validity should be confirmed by the parameter’s ability to separate steady from non-steady exercise. However, the 3MT seems to have the potential to predict and estimate the P-D relationship, whether compared to conventional methods via TT or TTE testing or via direct assessment in relation to intensity domains (Francis et al., 2010) or race predictions (Black et al., 2014), for example.

Indeed, the present analysis proves that CP can be accurately predicted by EP. An issue that seems to be problematic is the estimation of *W'*, not only in the view of the 3MT, but also in general when talking about the P-D relationship. Theoretically both, *W'* and WEP reflect the amount of work that an athlete is able to perform with the ATP/CP energy system and glycogen finite energy reserves (Moritani et al., 1981). Practically, whether *W'* and WEP really represent the same physiological quantity is a question that nearly seems impossible to be answered. Already in 1993 (Green & Dawson) it has been suggested that the term “anaerobic capacity” just describes a theoretical construct that is trying to measure in units of work but often fails to do so validly, as being prone to measurement errors. Its investigation appears to be difficult, if not impossible. *W’* remains a more variable measure in comparison to CP (Ferguson et al., 2010; Johnson et al., 2011; Pettitt, 2016), and so it will stay a challenge for future research.

Even though the WEP often fails to depict the same values of *W’*, it can still detect changes and improvements after for example training interventions reliably (Pettitt, 2016; Pettitt et al., 2019). Johnson et al. (2011) indicate that conventional methods seem more prone to high variability because of the extension of trials over several days. With that said, the 3MT can be seen as a more reliable assessment of *W’*. On the other hand, results of Triska et al. (2020) recently demonstrated that there were no significant differences in CP and *W’* and respective systemic responses between a multi-visit and a 30-min rest (single-visit) protocol.

To summarize, *W’* is sensitive to the testing protocol used (Triska et al., 2018), nutrition (Miura et al., 2000), prior high-intensity exercise (Vanhatalo & Jones, 2009), cadence in cycling (Vanhatalo et al., 2008b) and technique in other exercise forms (Cheng et al., 2012; Piatrikova et al., 2018), choice of TT or TTE method (Coakley & Passfield, 2018) and even mental fatigue (Salam et al., 2018). Maybe therefore, whether the conventional method is representing the “Gold Standard” for its determination or not is debatable.

2.4.2.2 Subject Groups

A limitation of the review depicts the insufficient implication of a specific target group. Most studies included different fitness levels which may in part explain different outcomes. Additionally, the experience levels differ as some studies indicate that only accustomed athletes were included and others state that even non-experienced subjects participated. However, this thesis suggests that in exercises that require less technique, like cycling and running, it appears to be easier to validly assess the P-D relationship with a 3MT then compared to rowing, swimming or cross-country skiing for example, where the exercise performance depends on high percentage of the technique rather than the general fitness level.

Although CP derived from traditional protocols and EP from 3MTs provided a similar mean power output or speed in most of the studies, there was often a large dispersion found when looking at individual determinations. This leaves the question, if the estimation of CP using the 3MT on an individual level makes sense. It is difficult to relate present findings to the mass, especially in other exercises apart from cycling, more studies are warranted to reason and underpin the findings.

2.4.2.3 Limitations, Harms and Chances

SMD were chosen, as the testing procedures and conditions from the studies differ. Additionally, there may arise differences when testing is carried out indoor compared to outdoor, or talking about on an electronical device (like ergometer or treadmill) instead of the "natural" way that an athlete is accustomated to (like the own bike, when rowing in water etc.). Also to note are the intraindividual conditions that differ from day to day, and a lot of influences that cause changes in the estimated parameters like from testing procedures (e.g. time and number of TT/TTE) or from the participants, like eating disorders and most importantly, the willingness to give a true all-out effort.

Recently the question arose if the conventional method still depicts the "Gold Standard". In his request for clarification, Pettitt (2019) characterizes a "Gold Standard" as the *"best available test without restrictions".* Obviously both concepts, the original 3MT and the conventional methods, are subjected to restrictions.

The main finding is that, for research reasons, the 3MT is a simple, easy, quick, reliable and valid estimation for the P-D relationship. Moreover, the 3MT showed also that it can be used to elicit $\dot{V}O_{2max}$. However, caution is recommended when using the determined parameters on individual level, especially when it comes to the prediction of *W'*.

2.4.3 Conclusions

When looking at the 3MT in its entirety, it can be concluded that it is a valid way to determine CP in most of the forms of endurance exercise. However, the subgroup analysis on cycling showed that there are significant differences between CP and EP.

Concerning the estimation of *W'*, results of the meta-analysis show that there were substantial differences between WEP and *W'*.

Partly, the lowered WEP values can be explained because of the slightly (but statistically insignificant) higher EP values. They can be explained that no true all-out effort happened in the onset of the 3MT.

In conclusion, the main reasons why the 3MT parameters may fail to validly depict the P-D parameters are:

The choice of (1) testing protocols (time courses, places, conditions and the related influences of cadence, stride or stroke mechanics and upcoming inertia or drag); (2) subgroups (number, fitness level and practice); (3) conscious or subconscious pacing that occurs.

Referring to the fitness level, there is a tendency for more accuracy in estimating the parameters of the P-D relationship when the athletes are moderately trained, but not on elite level. For such participants it may be easier to really target an all-out effort over the first few seconds of the 3MT. This can be summarized at least for exercise forms that require less technical skills. On the other hand, when the exercise form depends from a high-level technique, it seems that the estimation of the parameters using the 3MT is more precisely in accustomed, experienced athletes.

To conclude, the results of a 3MT should be taken with caution, but so should also be the results derived by any other method. True validity should be confirmed by the parameter's ability to separate steady from non-steady exercise.

3 METHODOLOGICAL APPROACH

3.1 Background of the P-D Relationship and prior Fatigue

Most of the performance tests are carried out under rested conditions. However, fatigue induced changes to the P-D relationship seem to be of important interest when it comes to endurance events as for example marathons. The question, how prior exercise affects the P-D relationship, has been attracting researcher’s interest since the early 2000s.

Back then, the effects on the time course of the pulmonary oxygen uptake response have been comprehensively investigated. Vanhatalo and Jones (2009) sum up that prior high-intensity load, either in the form of short-term sprinting or prolonged CWR-exercise, increases oxygen uptake in the first 1-3 min of subsequent exercise (Bangsbo et al., 2001; Burnley et al., 2002; Burnley et al., 2001; Burnley et al., 2000; Jones et al., 2003; Sahlin et al., 2005) and that this effect can be sustained for up to 45 min. In terms of fatigue, Jones et al. (2003) demonstrated that the elevated blood lactate concentration of prior heavy exercise (<CP) resulted into an increased TTE during subsequent perimaximal exercise. They state that this was likely due to enabling greater aerobic contribution to the energy requirement. Carrying this over to the terms of the P-D relationship, they report that prior heavy-intensity has no effect on CP but tends to increase *W’*, resulting into enhanced performance.

Triska et al. (2020) on the contrary did not find any priming effect of exhaustive TT in a 30-min rest protocol to determine the P-D relationship. The TT (10, 5, and 2 min in that order interspersed with 30 min rest) did neither affect *W’*, CP, nor systemic responses when compared to a multi-visit protocol.

Ferguson et al. (2007) demonstrated that prior exercise >CP has no effect on CP but distinctly reduces *W’* and therefore impairs exercise performance. Consistent with this and by being the first using the “novel” 3MT, Vanhatalo and Jones (2009) show that *W’*, but not CP, is sensitive to a bout of prior sprint exercise of 30 s. TTE was shortened and therefore exercise was impaired. Also with the use of a 3MT, Simpson et al. (2012) demonstrated that there were no differences in estimated EP values, but WEP was significantly lower ($p < 0.05$) after a prior 2 and 4 min severe-bout compared to a control trial or after 6 min of moderate or heavy intensity.

As the effects of short time prior exercises were well examined, the question arose, how the P-D parameters change in longer prior efforts. Therefore more recently, Clark et al. (2018) extended the time of the prior exercise mode to 2 h of heavy-intensity (i.e. > LT but < CP) cycling. These authors showed that both, EP and WEP, were significantly lower ($p < 0.01$ and $p < 0.05$ for EP and WEP, respectively) compared to values derived from a 3MT completed in rested state. The diminished $\dot{V}O_{2max}$ value in a further testing at an intensity domain above the fatigued EP value subsequent to the prior 2 h and the fact that the majority of the participants were not able to complete more than 20 min of exercise intensity below fatigued EP allude to the presumption that the physiological and functional definition of EP in fatigued state appears to be fundamentally different to that in rested state. This finding may be of important interest in longer endurance events.

As these findings were only underpinned in terms of cycling (Clark et al., 2019b; Clark et al., 2019a) so far, the question arises if the P-D parameters change the same way when it comes to running. Therefore, the following methodological approach based on the study of Clark et al. (2018) and replicated into running will be presented. Moreover, the results of a pilot testing will be shown and discussed.

3.2 Methods

3.2.1 Participants

Similar to previous work of Clark et al. (2018), a number of 12 participants is desirable. The age of the participants should be in-between 18 and 40 years. They should train regularly for three years, ideally train to compete, and be familiar with > 2 h of running and high intensity exercises. Participants should be healthy and free of any injury.

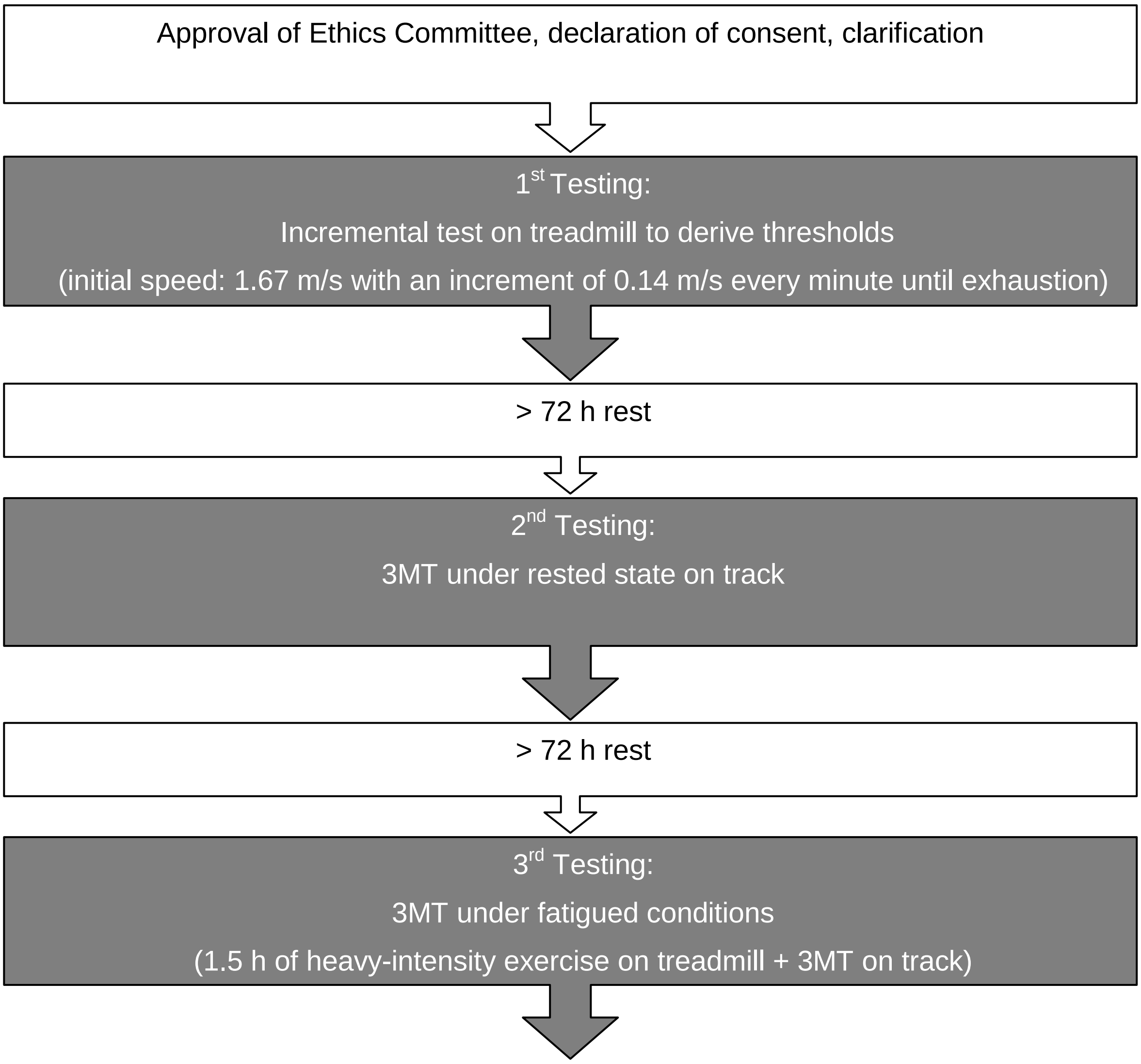
3.2.2 Experimental Protocol

In total, each participant volunteers for four testing occasions, whose should be separated by a minimum of 72 h. During the first visit, participants should complete an incremental test exercise on a treadmill (saturn, h/p/cosmos, Traunstein, Bayern) for the determination of $\dot{V}O_{2max}$ and GET (MetaMax3B-R2, Cortex Medical GmbH, Leipzig, Deutschland). The GET should be defined as: 1) the first disproportionate increase in carbon dioxide output relative to oxygen uptake; and 2) an increase in the ventilatory equivalent for O_2 (VE/VO_2)

with no increase in the ventilatory equivalent for CO2 (VE/VCO_2), as proposed by Beaver et al. (1986).

The initial speed is 1.67 m/s (6 km/h) and will be incremented every minute by 0.14 m/s (0.5 km/h) until exhaustion. Additionally, the RCP will be determined, depicting the $\dot{V}O_2$ value corresponding to the point of departure from linearity of the VE/VCO_2 relationship (Beaver et al., 1986).

As in the study of Clark et al. (2019a), the participants undergo a familiarization 3MT. It takes place after the completion of the incremental test, with 30 min of rest in-between testings.



> 72 h rest

4rd Testing:
3MT under fatigued conditions
(1.5 h of heavy-intensity exercise on treadmill + 3MT on track)

Fig. 17: The order of performance testing protocols and resting times.

On visit 2, participants complete a 3MT to determine ES and DES under rested conditions. The 3MT will be carried out on a 400-m track and participants should be verbally encouraged for an all-out effort. Instructions should be given to reach maximal speed as fast as possible and to maintain the all-effort throughout the test, without getting informed about the elapsed time. ES will be calculated as the mean speed over the last 30 s of the 3MT, and DES will be calculated as the distance covered above ES during the test. GPS data will be recorded with a wearable device (Garmin Smart Watch), and the pulmonary gas exchanges with a mobile spirometry. Additionally, due to the inaccuracy of the GPS system on track, there will be video recording and cones will be placed every 10 m to collect the distance that has been covered.

On visit 3 and 4, participants complete a after a prior heavy-intensity exercise bout (fatigued 3MT). To test the reliability, the test should be carried out twice. The heavy-intensity exercise takes place on the treadmill with the speed calculated as the speed at the GET plus 25% of the difference between the GET and the ES tested on visit 2, which was found out by Clark et al. (2018) to be in the heavy intensity domain. As follows, this preload intensity domain will be called Delta25 (Δ25%). A duration of 1.5 h was chosen as the 2 h of cycling in the study of Clark et al. (2018) may be too long in terms of running.

Based on Jones and Doust (1996), a 1% grade should be utilized on the treadmill to overcome the issue that the lack of air resistance when running indoor results in a lower energy cost when compared with running outdoor on track at the same speed.

3.3 Results of Pilot Testing

The pilot testing was carried out with a 24 year old female distance runner (height: 156 cm; weight: 51 kg, $\dot{V}O_{2max}$: 50.1 ml/min/kg) in February 2020. This athlete trained regularly for more than 3 years and has experience in competitive running (half-marathon) and running above 2 h.

3.3.1 Incremental test

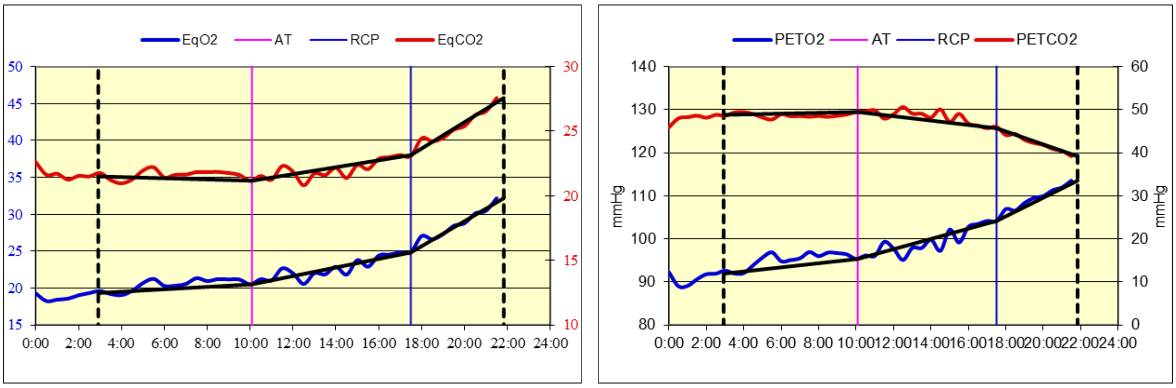


Fig. 18: Determination of the first and second ventilatory threshold using VE/$\dot{V}O_2$, VE/VCO_2 (left panel), and $PETO_2$ and $PETCO_2$ (right panel).

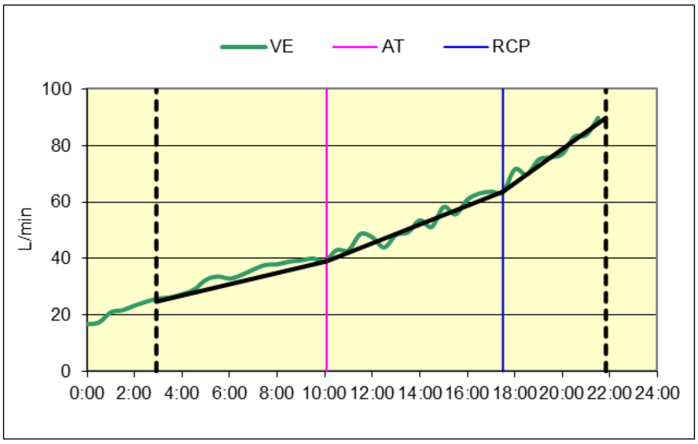


Fig. 19: Determination of the first and second ventilatory threshold using VE.

On the first visit, the GXT was carried out on a treadmill in the Austrian Institute of Sports Medicine (ÖISM). The initial stage was 1.67 m/s (6 km/h) with an increment of 0.14 m/s (0.5 km/h) every minute. The test was terminated at a speed of 4.58 m/s (16.5 km/h).

The first threshold (AT) was defined at the speed of 2.92 m/s (10.5 km/h), the second (RCP) was found to be at 3.97 m/s (14.3 km/h). The $\dot{V}O_{2max}$ was 50.1 ml/min/kg. All values of the thresholds and maximal values can be seen in Table 2.

Table 2: Thresholds and Peak Values of the Incremental Test.

Measure	Unit	AT	RCP	Max
velocity	km/h	10.5	14.3	16.5
time/km	mm:ss	05:41	04:12	03:38
$\%V_{max}$	%	63.9	86.4	100
HR	b/min	159	186	199
$\%HR_{max}$	%	79.8	93.5	100
VO_2	ml/min	1,749	2,374	2,555
$\dot{V}O_2$	ml/min/kg	34.29	46.55	50.10
$\%\dot{V}O_{2max}$	%	68.4	92.9	100
energy expenditure	kJ/min	36.7	49.9	53.7
economy	ml/min/km	195.17	196.00	182.19

AT = first ventilatory threshold; RCP = second ventilatory threshold; Max = maximum values; V_{max} = maximum velocity; HR = heart rate; VO_2 = absolute oxygen uptake; $\dot{V}O_2$ = relative oxygen uptake.

After the completion of the incremental test and with 30 min of rest in between, a familiarization 3MT was carried out.

3.3.2 3-Minute All-Out Test

The 3MT under rested conditions devoted an ES of 4.33 m/s, or 15.6 km/h (3:50 min/km), respectively. DES was calculated to be 71 m. When having a look at Fig. 20, the deviations of the fall in speed within the first 30 s might be due to errors of the GPS signal because of trees near the track. Apart from this, one can see the typical curvilinear velocity pattern: The all-out effort is visible as peak PO is attained within the first 10 s and PO reaches a plateau in the last 30 s of the test.

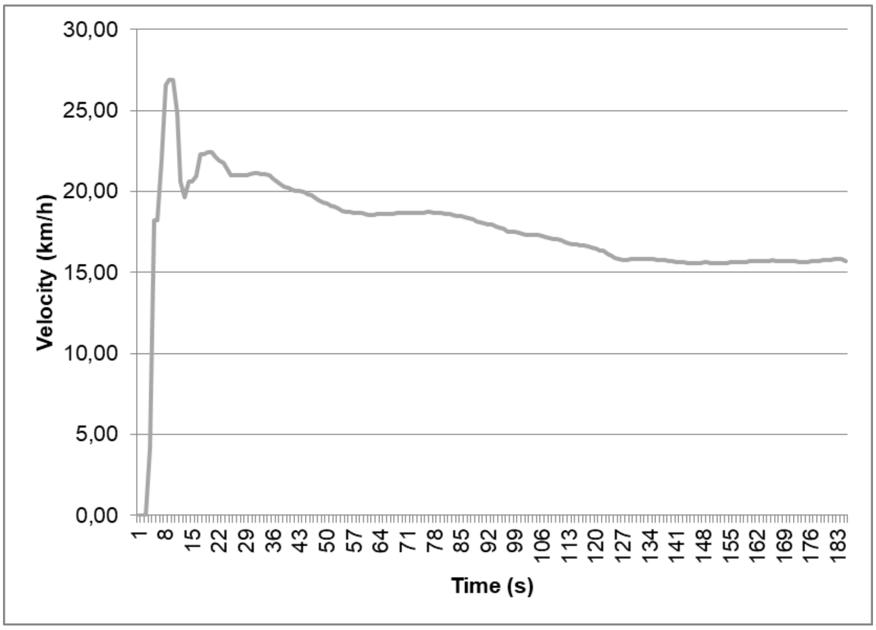


Fig. 20: 3-Min All-Out Test Rested State.

3.3.2.1 Calculation of the Preload

Based on the results of the first visits, Δ25% was computed to be 3.25 m/s (11.7 km/h) (25% of the difference of ES = 4.33 m/s and AT = 2.89 m/s added to the AT):

$$\mathbf{(ES - AT) \times 0.25 + AT = \Delta 25\%}$$

$$(4.33 - 2.89) \times 0.25 + 2.89 = 3.25$$

3.3.2.2 3-Minute All-Out Test in Fatigued Condition

Due to the lockdown, testing was carried out at home instead of a track. The 3MT shortly after 1.5 h of heavy intensity running on a treadmill devoted an ES of 4 m/s, or 14.4 km/h (4:10 min/km), respectively. DES was calculated to be 109 m. The testing took place on a flat asphalt ground. Fig. 21 depicts the time course of the 3MT and one can see the typical curvilinear power profile, with the maximal velocity being attained within the first 10 s and the last 30 s representing the ES.

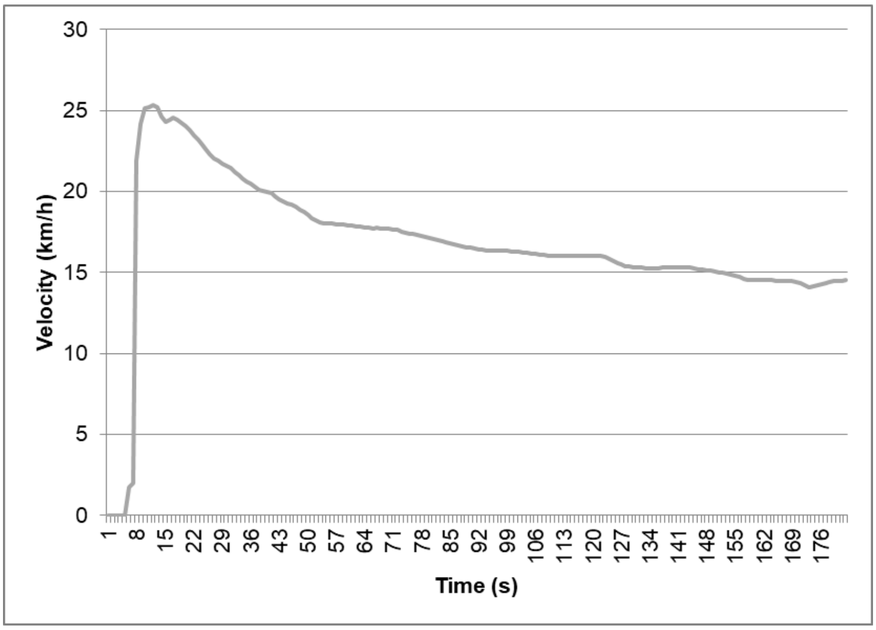


Fig. 21: 3-Min All-Out Test Fatigued State.

3.3.3 Difference between Conditions and Analysis of the Parameters

When having a look at the differences between testing conditions, there is an 8% reduction of ES in the fatigued compared to the rested state. In terms of DES, there is a 54% increase. Maximal velocity was 0.42 m/s (6%) lower after 1.5 h of preload.

Table 3: Values of the Rested and the Fatigued State and their absolute and relative Differences.

Measure	Rested	Fatigued	Absolute Difference	Unit	Relative Difference in %
ES	4.33	4.00	-0.33	m/s	-8%
DES	71	109	38	m	+54%
V_{max}	7.47	7.06	-0.41	m/s	-6%

ES = end-test speed; DES = distance above end-test speed; V_{max} = maximum velocity.

The reduction of ES is consistent with the findings of Clark et al. (2018), who also reported a loss of 8%. However, unlikely to their results, the pilot testing reveals an increase of DES of 54%.

When comparing it to the study of Jones et al. (2003), the current finding shows similar results as they found out that anaerobic capacity might be positively influenced by prior heavy activity. The performance of 6 min of prior heavy-intensity led to an increase in the time to exhaustion during subsequent perimaximal exercise. Then again, as the 1.5 h heavy intensity on the treadmill may also evoke several signs of fatigue, this finding may be debatable relating the same findings to this long duration.

Another explanation of the increase in DES in fatigued state might be the fact that the value of the rested state greatly underestimated DES or the "real *D'*", as can be seen below when comparing the derived parameters to PR. Moreover, account should be taken of the results of the meta-analysis, indicating that *D'* and DES cannot be used interchangeably.

However, results should be interpreted with caution, as the local conditions (e.g. surface, altitude, inclination) between testings differed due to the lockdown. In the testing of the rested 3MT, the athlete was encouraged to give an all-out effort, whereas the second testing was carried out alone. Additionally, it is important to be aware that there will always be some error in the estimation of the P-D relationship as CP varies slightly from day to day in the same subject, as shown by Smith and Hill (1993).

3.3.4 Estimation of CS according to Personal Records

To test the practicability of the estimated parameters, values derived from a 3MT running test will now be compared to CS and *D'* gained from personal records (PR) (Jones & Poole, 2009; Pettitt, 2016), computed by the free computer program "Golden Cheetah". The program needs two personal bests to estimate the P-D parameters by using Monod and Scherrer's (1965) model. The estimation requires times where the first PB should lie within 3-5 min and the second one between 15-60 min.

To test the difference how the time course or alternatively the distance chosen influences the estimation, two trials were conducted:

> When entering PR1 as 1,000 m in 3 min 25 s, and PR2 as 5,000 m in 18 min 55 s, the estimated CS was computed to be 3:52 min/km or 15,52 km/h or 4.31 m/s, respectively, and the estimated *D'* reveals to be 118 m.

When entering PR1 as 1,000 m in 3 min 25 s, and PR2 as 10,000 m in 39 min 30 s, the estimated CS was computed to be 4 min/km or 15 km/h or 4.17 m/s, respectively, and the estimated *D'* reveals to be 148 m.

This difference in the derivation of the P-D parameters should once again show the variability and importance of the methodology used. In this sense it may be important what the aim of an athlete is. Seeing it in the light of longer lasting endurance events such as half marathons and marathons, values derived from longer durations where fatigue is playing a role in the estimation may be the better and more fitting choice.

3.3.5 Comparison of the Rested and Fatigued 3-Min All-out derived Parameters to PR and RCP values

CP and its relation to the second threshold has been studied in various ways (Bergstrom, Housh, Zuniga, Traylor, Camic, et al., 2013; Broxterman et al., 2015; Cross & Sabapathy, 2012; Dekerle et al., 2003; Pessoa Filho et al., 2012). Broxterman et al. (2015) summary that CP from conventional methods and RCP from incremental tests may occur at similar intensities, and that both parameters demarcate the lower boundary of the severe-intensity domain. By using the 3MT, Bergstrom et al. (2013) compared EP from 3MT to the power outputs associated with the RCP and found out that they were nearly ident.

The results of the meta-analysis from Galán-Rioja et al. (2020) show that the RCP significantly differs from CP but significantly correlates. RCP overestimated CP by 6% (Fig. 7), that is the outcome of the subgroup analysis of three studies. However, the results of the pilot testing reveal the contrary, RCP underestimated CP determined by any method.

In Table 5 all representatives of the P-D relationship that have been determined are summarized. The pilot testing suggests that the 3MT slightly overstates PR, but comes close to the estimation of CS. The PR using the shorter time/distance seems to match better with the rested 3MT, whereas the PR using the longer one has a tendency to the fatigued 3MT ES. Consistent with the results of the meta-analysis, DES of both 3MTs is lower compared to conventional estimated *D'*. Interestingly, RCP of the GXT seems to come close to fatigued 3MT.

Table 4: Summary of Results from the Pilot Testing: Representatives of the P-D Relationship determined by different Methods.

Method	Results of CS in m/s (km/h)	Results of *D'* (m)
3MT	4.33 (15.6)	71
$3MT_{fatigued}$	4.00 (14.4)	109
PR_{short}	4.31 (15.5)	118
PR_{long}	4.17 (15.0)	148

CS = critical speed; D' = distance above CS; 3MT = 3-min all-out test; PR = personal records.

3.4 Discussion

3.4.1 Test Execution

The pilot testing and reproduction of the cycling-study of Clark et al. (2018) is of significant value as it shows that the results are likewise in running, at least in the aerobic parameter. However, more tests and results are warranted to draw conclusions for the totality.

In this special situation with the unexpected lockdown, a limitation of the completion of the fatigued 3MT was that it took place in a different environment than the rested one. The main problem depicts the fact that the recording was only made with GPS of the smart watch (Garmin Forerunner), but the test in rested state has shown that it is necessary that, additional to tracking the GPS data, the run is filmed, so that the actual distance that will be covered can be compared and, if needed, adjusted.

3.4.2 Comparison of derived P-D Parameters

As CP and its relation to the second threshold has been studied in various ways before, this was the first approach to compare it with a fatigued state.

CP and RCP occur at similar intensities and both parameters demarcate the lower boundary of the severe-intensity domain (Broxterman et al., 2015). However, just recently, Galán-Rioja et al. (2020) showed that they cannot be used interchangeably. The study of

Broxterman et al. (2015) demonstrates a sufficient degree of variability between CP and RCP, so that the estimation of CP from RCP should be attempted with caution.

To date, it is unclear if a high degree of variability is due to measurement errors (either in CP or RCP estimation, or even both), or if this leads to that the parameters may not represent the same physiological responses.

Moreover, the results of the comparison suggest that there may be not only “that one CP” but to see it more as a domain instead of a specific value. The parameters of the P-D relationship are sensible to the length of exercise and fatigue. CS using PR may be an easy-to-use tool, although not always being accurate. To conclude, all estimations have their strengths and weaknesses, suggesting that there is not one “Gold Standard” to use, but it is of more importance to have a look at what the aim of a testing is to make it specific.

4 GENERAL DISCUSSION

Knowing the cycling power or the running speed that is leading to the maximal sustainable oxidative metabolic rate is of important interest when it comes to guiding athletic training and predicting race performances. Endurance exercise training is leading into profound adaptations of the cardiorespiratory and neuromuscular systems, enabling a better regulation of the muscle metabolism by enhancing the delivery of oxygen to the mitochondria. This resulting improvement in performance is manifested as the rightward shift of the P-D curve, which again empowers athletes to endure a given exercise intensity longer, or to exercise at a higher intensity for a given duration (Jones & Carter, 2000; Jones et al., 2010; Vanhatalo et al., 2011).

In athletic performance, all track events starting with 800 m are typically categorized to be endurance events. The “type” of endurance that is needed for 800 m of running is obviously very different to that required for example for a marathon (Jones & Poole, 2009). Also, it is very important in which intensity domain an exercise is done and how long it will be kept, as these mechanisms determine the fatigue that is again affecting the performance (Poole et al., 2016).

It has been reported that elite athletes sustain ~96% of CS during a marathon race, the percentage is of determination using short race distances (Jones & Vanhatalo, 2017). Therefore, it might be said that the (endurance) race performance happens at the upper end of the heavy-intensity domain. Taking now in account that the CS during running declines as has been shown in this thesis and in the study of Clark et al. (2018), it is likely that the value of 96% is an under-estimation of the actual effort done. If a constant speed during a long-distance race is maintained by an athlete, he or she will gradually get closer to and eventually exceed CS and consequently deplete *D’*.

Recently, Smyth and Muniz-Pumares (2020) evaluated raw training data from more than 25,000 recreational marathon runners. The authors confirm that estimations of CS from training data successfully predict marathon performances and therefore provide useful pacing information. In their study, runners completed the marathon at 85% (± 14%) CS. Faster runners, talking about durations of ~150 min for the marathon, were competing at speeds closer to CS (93% CS) than runners who completed the marathon in ~360 min (79% CS). Moreover, runners who completed the first half of the marathon at > 94% of their predicted CS were more likely to slow down by more than 25% in the second half.

A lot of studies investigated the P-D relationship, with the use of the 3MT or any other method, in terms of cycling. However, not much evidence of other sport types is available so far. Although a lot of results can be adopted into other exercise formalities, caution is warranted when comparing one form with another. This includes technique skills, muscles that are required and therefore their respective energy systems. To give advice to broader exercise modalities, the thesis may offer not enough evidence.

It is of highly importance that a test is chosen that actually fits the needs of the athlete. In order to decide which testing should be carried out, it should be clear which aim is targeted. Also, if the conclusions drawn from studies should help athletes to become better in their sporting type, it may be of limited value if tests are carried out with habitually active subjects that are unused to the sporting types. Future research should consider this and advices should be made specific and given with caution.

It may be possible that CP represents not only a specific value, but also a small domain (Ozkaya et al., 2020) and might be a transition phase rather than a threshold (Pethick et al., 2020).

Concluding, it should be considered that asking a subject to exercise exactly at his or her estimated CP or CS runs the risk that the intensity will be above or below the actual warranted intensity.

5 GENERAL CONCLUSIONS

In order to determine the P-D parameters, the “Gold Standard” seems to be the most accurate method. However, the results of the thesis suggest that the 3MT has the potential to validly assess CP and CS in different models of exercise, but it failed to do so in *W’* or *D’*.

Each and every method brings along its measurement errors and weaknesses. But also, so do all have their strengths and advantages. The 3MT has not only the advantage of requiring only one testing, in the light of mathematics, its application minimizes conventional CP errors (like the chosen equation, trials and duration and even intraindividual differences) since the parameters of the P-D relationship are directly obtained only from one single test. The derived parameters can be useful for example to detect changes in training progresses and as shown EP comes close to the conventional CP, but WEP should be taken with caution. It has been demonstrated that *W’* is neither an independent, nor a fixed amount and that it can be refilled again, what makes it hard to measure. As simple as the P-D relationship once appeared to be, there is a lack of proper understanding of the behavior of *W’* so that many attempts have already been made to address this gap, but with only limited success.

Nevertheless, the P-D relationship depicts a powerful framework in which one can explore the physiological mechanisms of fatigue and that without great cost or effort. CP demarcates the threshold of oxidative metabolism and represents the upper boundary for progressive neuromuscular fatigue and can therefore be seen as “fatigue threshold”. In regard of the recent findings (Jones et al., 2019; Ozkaya et al., 2020; Pethick et al., 2020; Smith & Jones, 2001) one can consider that CP is not only limited to depict “one value”, but that it can vary and be expressed in different ways.

The thesis shows that the P-D relationship is a well-integrated tool in several models of exercise, despite each mode brings along its certain requirements. The reproduction of the study of Clark et al. (2018) revealed similarities when carrying out a single pilot testing. However, there were also differences and whether they happened due to the changed sport type (cycling to running) or other reasons have to be investigated.

Regarding different boundaries and especially the second boundary that demarcates the heavy from the severe domain, CP, RCP and MLSS have been considered synonymous. However, Galán-Rioja et al. (2020) showed that although being significantly correlated, CP differs significantly from each metabolic and ventilatory threshold.

When seeing the P-D relationship in a broader sense by including the fatigue mechanism as this plays a key role in (longer) endurance sports, the following can be summarized:

As intensity increases, the relative importance of peripheral factors seems to increase, whereas in decreased intensity, it is more likely that the central and psychological factors play a more important role (Burnley & Jones, 2018). This depicts also the fact that its determination might be affected by for example nutrition and carbohydrate storage. However, how fatigue influences firstly the detection of the P-D parameters and secondly its practical application should get more into scientific focus.

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STATUTORY DECLARATION

"I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources."

Vienna, January 2021 Nadine Dorner