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Critical power estimation provides a good approximation of the power output associated with the maximal metabolic steady state in both trained and untrained participants

by

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Abstract

Critical power (CP) estimation is a well-established method to identify the power output (PO) associated with the maximal metabolic steady state (MMSS) of exercise. CP estimation requires multiple time to task failure (TTF) trials and the precision of this evaluation in untrained individuals could be questionable due to their inexperience with performing highly demanding efforts to volitional exhaustion. Thus, the goal of this study was to compare whether the accuracy of CP to approximate the MMSS was affected by the training status of the individuals. Participants underwent: i) a ramp incremental test to task failure to determine maximal oxygen consumption ($\dot{V}O_{2max}$) and peak PO (PO_{peak}); ii) a series of 4-5 TTF trials at average POs ranging from 70 to 90% of PO_{peak} performed on separate days, to obtain TTF durations of ~3-15 min for CP estimations; iii) 2-3 30-min constant PO rides to establish MMSS. The PO associated to CP was significantly greater than that associated to MMSS in both untrained (155±39 W vs. 147±34 W, respectively) and trained (233±37 W vs. 225±39 W, respectively) individuals ($F = 13.2$, p = 0.001, $\eta^2 = 0.375$, effect size d = 0.14). Despite this, no significant differences in the PO at CP and the PO at MMSS were observed between the untrained and trained groups (bias = 7.5 W for both groups; $F = 0.01$, p = 0.99, $\eta^2 = 0.001$; statistical power = 99%) and for both groups, the biases were significantly greater than 0 (untrained z = 2.57; trained z = 2.95). The 95% CI for the LOA were -13 to 28 W, and -11 to 26 W for untrained and trained, respectively. These findings indicate that, despite a significant (albeit small) difference between CP and MMSS, the CP model provided a close approximation of the PO associated with the MMSS in both untrained and trained participants. This indicates that the quality of the CP model was not affected by training status, which suggests that previous experience with highly demanding exercise is not a key component of the quality of the prediction.

Preface

This thesis is original, unpublished, independent work by Brynn Lindstrom, Pablo Fleitas Paniagua, Gabrielle Marinari, Dr. Letizia Rasica, Dr. Alessandro Zagatto, and Dr. Juan Murias. The research conducted, presented, and discussed in Chapters III-V was approved by Ethics Certification REB18-0916 issued by the University of Calgary Conjoint Health Ethics Board for the project “The influence of the slope of the ramp on physiological markers of exercise intensity during incremental tests to exhaustion”.

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List of Symbols, Abbreviations, and Nomenclature

Abbreviation	**Definition**
$\dot{V}O_{2max}$	Maximal oxygen consumption
HR_{max}	Maximum heart rate
PO_{peak}	Peak power output
GET	Gas exchange threshold
MMSS	Maximal metabolic steady state
CP	Critical Power
MLSS	Maximal lactate steady state
$[La^-]_b$	Blood lactate concentration
$\dot{V}O_2$	Rate of oxygen consumption
PO	Power output
MRT	Mean response time
LT	Lactate threshold
RCP	Respiratory compensation point
ATP	Adenosine triphosphate
H^+	Hydrogen ions
W'	W Prime
CP_{2HYP}	Two-parameter hyperbolic model of critical power
TTF	Time to task failure
T_{lim}	Duration a preestablished power output could be tolerated
CP_{lin}	Linear critical power model, product of power output and time
W	Work
$1/T_{lim}$	Inverse of time
$CP_{1/Tlim}$	Linear critical power model, relationship between power and inverse of time
CP_{3MIN}	Critical power derived from a 3-minute all out test
P_{max}	Maximal instantaneous power
CP_{3HYP}	Three-parameter model of critical power
LOA	Limits of agreement
W	Watts
$\dot{V}O_2/W$	Functional gain of oxygen consumption
RI	Ramp-incremental
$MLSS_{pred}$	Predicted maximal lactate steady state
$MLSS_{obs}$	Observed maximal lactate steady state
$\dot{V}O_{2peak}$	Peak oxygen consumption
SRS	Step-ramp-step
MOD	Moderate-intensity step transition
HVY	Heavy-intensity step transition
$M\dot{V}O_{2ss}$	Highest submaximal rate of oxygen consumption at steady state
$MLSS_{5-30}$	Maximal lactate steady state; minutes 5-10
$MLSS_{10-30}$	Maximal lactate steady state; minutes 10-10
$MLSS_{15-30}$	Maximal lactate steady state; minutes 15-10
$MLSS_{20-30}$	Maximal lactate steady state; minutes 20-10
$MLSS_{25-30}$	Maximal lactate steady state; minutes 25-10

CSEP	Canadian Society of Exercise Physiology
GAQ	Get active questionnaire
RPE	Rating of perceived exertion
Dyspnea	Intensity of breathlessness
Pain	Exercising leg pain
HR	Heart Rate
rpm	Revolutions per minute
SEE	Standard error estimates
O_2	Oxygen
CO_2	Carbon dioxide
N_2	Nitrogen
$\dot{V}_E$	Pulmonary ventilation
$\dot{V}CO_2$	Carbon dioxide output
RER	Respiratory exchange ratio
$PetO_2$	End tidal pressure of oxygen
$PetCO_2$	End tidal pressure of carbon dioxide
$\dot{V}_E/\dot{V}O_2$	Ventilatory equivalent ratio of oxygen
$\dot{V}_E/\dot{V}CO_2$	Ventilatory equivalent ratio of carbon dioxide
$\dot{V}CO_{2max}$	Maximal carbon dioxide output
RER_{max}	Maximal respiratory exchange ratio
ANOVA	Analysis of Variance
SD	Standard deviation
$[La^-]_{bmax}$	Maximal blood lactate concentration
$RI\text{-}PO_{peak}$	Peak power output derived from the ramp-incremental test
$[La^-]_{bpeak}$	Peak blood lactate concentration
RPE_{peak}	Peak rating of perceived exertion
HR_{peak}	Peak heart rate
$RI\text{-}\dot{V}O_{2max}$	Maximal oxygen consumption derived from the ramp-incremental test
$RI\text{-}HR_{max}$	Maximum heart rate derived from the ramp-incremental test
R^2	*R*-Squared
SWC	Smallest worthwhile change
SRS-MMSS	Step-ramp-step derived maximal metabolic steady state
CI	Confidence interval
COPD	Chronic obstructive pulmonary disease

Chapter I: Introduction

Exercise intensity is a key component of exercise training and serves as a blueprint for eliciting a given metabolic disruption for exercise prescription and testing, that results in more predictable acute physiological responses and chronic adaptations to training (Iannetta et al., 2019). Although different approaches can be used to prescribe exercise intensity, current guidelines make recommendations based on normalized fixed percentage of maximal individual values such as $\dot{V}O_{2max}$, maximum heart rate (HR_{max}), and PO_{peak}, typically derived from a ramp-incremental exercise test (Garber et al., 2011). However, the limitations of these approaches to capture the true metabolic disruptions elicited by the exercise have been highlighted, as the same percent of a maximal/peak values can place different individuals within different exercise intensity domains, and thus different level of metabolic stress (Iannetta et al., 2019).

To circumvent this issue, the use of exercise intensity domain specific training intensities has been recommended (Inglis et al., 2024). Using this model originally proposed by Whipp et al. (1996), exercise intensity can be separated into three exercise intensity domains: moderate, heavy, and severe, separated by two exercise intensity boundaries. Whereas the gas exchange threshold (GET) separates the moderate from the heavy intensity domains (Beaver et al., 1985; Whipp et al., 1982), MMSS is recognized as a physiological threshold that demarcates the boundary between the heavy and severe intensity domains of exercise (Keir et al., 2018). Identifying the MMSS has been shown to be a key component in understanding the acute adjustments and chronic adaptations to exercise training (Azevedo et al., 2021; Iannetta, Inglis et al., 2018; Inglis et al., 2024; Keir et al., 2018; Maturana, F.M. et al., 2021; Weatherwax, R.M. et al., 2018).

Two commonly used approaches to estimate the work rate associated to the MMSS are the use of the CP model and the maximal lactate steady state (MLSS) model. The CP model is based on the hyperbolic relationship between exercise intensity and duration within the severe domain, with the asymptote of this relationship representing the highest intensity of exercise that can be sustained relying almost exclusively on oxidative metabolism (Poole et al., 2016; Jones et al., 2010). On the other hand, the MLSS protocol also represents the upper limit of exercise that be sustained primarily by aerobic resynthesis of energy but is based on physiological evaluations of blood lactate concentration ($[La^-]_b$) (Craig et al., 2016). Although debate exists on what approach might provide the most accurate approximation of the work rate associated to the MMSS (de Lucas, 2018; Keir et al., 2021; Mattioni Maturana et al., 2018), a recent study has provided insights into the possibility of reconciling the outcomes from these two models by following specific methodological approaches (Iannetta et al., 2021; Keir et al., 2018; Mattioni Maturana et al., 2016). Whereas the MLSS approach offers physiological data that can add confidence in the determination of the metabolic disruption of the exercise, the CP model has the advantage of not only providing the work rate corresponding to the MMSS, but also the W' (Iannetta et al., 2021; Poole et al., 2006). Identifying W' can be useful as it has implications on an individual's work capacity above CP (Bishop, Jenkins & Howard, 1998), which adds practical value to the model in terms of exercise intensity prescription, especially during interval training within the severe intensity domain. However, one potential criticism to the CP model is that accurate estimation of the power output (PO) at MMSS relies on the performance of efforts that are intended to result in maximal responses to exercise including the achievement of a $\dot{V}O_2$ response that represents at least 95% of $\dot{V}O_{2max}$ and depletion of W' (Black et al., 2017; Keir et al., 2016; Poole et al., 2016). This type of effort might be more challenging to be completed by participants who are less experienced with performing highly demanding exercise (e.g., untrained participants), which could negatively affect the predictive value of the model and add some extra measurement error in CP beyond the already accepted ~5% (Black et al., 2017; Hill, 1993). In fact, previous experience with performing these highly demanding efforts has been mentioned previously by Hill (1993) as a consideration when selecting a model to estimate CP. Further, research from Keir et al. (2018) has also recently supported this notion, giving relevance to exploring this concept.

Thus, the goal of this thesis was to compare the PO of the estimated MMSS to the PO derived from the CP model in two groups of participants: i) untrained individuals who are unexperienced with performing efforts that are intended to result in maximal responses to exercise; and ii) moderately- to well-trained individuals who were used to consistently performing such efforts. We hypothesized that, whereas trained individuals would display CP values that were similar to those of MMSS, untrained individuals would show poorer estimations of CP in relation to MMSS.

Following Chapter I, Chapter II will include an in-depth review of current literature to grasp the understanding of various topics related to CP and its precision in estimating the work rate associated to the MMSS. Chapter III will follow including the methodological approaches utilized to investigate whether CP provides a good approximation of the power output associated with the MMSS in both trained and untrained participants. Chapter IV will sum up the results of the investigation, followed by Chapter V discussing them. Chapter VI will serve as the final chapter summarizing the limitations, considerations, and future implications.

Chapter II: Literature Review

2.1. Current Methods for Exercise Prescription Used in Research and Clinical Settings

Exercise intensity represents a key element of exercise physiology, providing a valuable blueprint that can be used to perform certain aerobic tests, examine physiological responses, understand adaptations to exercise training, and to prescribe exercise (Iannetta et al., 2020).

2.1.1 Percent of maximal response approach

The most commonly used current approach to prescribe exercise intensity and to determine different exercise training zones entails normalizing values based on percentages of maximal values, typically obtained during incremental tests to task failure (Iannetta et al., 2019; Keir et al., 2018). $\dot{V}O_{2max}$, which is determined through cardiopulmonary incremental exercise testing, is considered as the gold standard for evaluating cardiorespiratory fitness and to assign exercise intensity for endurance training. However, this method has some clear limitations. For example, in addition to the need for expensive equipment and specialized testing procedures, the inability to know one's $\dot{V}O_2$ during daily performed exercise invalidates the possibility of estimating a given percent of its maximal value as a reference point (Iannetta et al., 2020). Then, other methods that are used include the measurement of other maximal physiological outcomes, such PO_{peak} and HR_{max}, so that a percent value of these outcomes can then be connected to a given $\dot{V}O_{2max}$ percentage (Iannetta et al., 2020). Although these alternative methods to circumvent the lack of metabolic data during regular training have been used for a long time and are considered to be appropriate for exercise prescription, recent literature indicates that there are evident limitations that surround them when trying to properly quantify the metabolic stress of exercise (Iannetta et al., 2020).

A limitation to utilizing PO_{peak} percentage taken from an incremental test is that this outcome is most likely to produce an overestimation of the $\dot{V}O_2$ associated to any constant work rate exercise at a given PO aiming to elicit a given percentage of $\dot{V}O_{2max}$ during exercise (Iannetta et al., 2020). The reasons for this phenomenon are related to two main factors: i) there is a time lag between the increase in muscle $\dot{V}O_2$ to be expressed at the site of measurement that is typically not considered when assigning a PO value to a given $\dot{V}O_2$ response (Iannetta et al., 2020; Keir et al., 2018; Ozyener et al., 2001). During ramp incremental tests, this time is referred to as the mean response time (MRT); ii) the increase in $\dot{V}O_2$ is not linearly related to the increase in PO during constant work rate exercise performed within different exercise intensity domains, despite the seemingly linear relationship between these two outcomes during ramp incremental testing, this is because of the $\dot{V}O_2$ slow component (Iannetta et al., 2020; Keir et al., 2018; Ozyener et al., 2001).

When referring to HR_{max} percentage there are a few factors to consider. For example, with the presence of the cardiac “drift”, there is variability in HR responses during constant work rate exercise of any intensity, making a steady state HR response somewhat elusive as it increases with exercise duration even when the metabolic rate remains constant. This in turn affects the precision of this method to associate a single percent of HR_{max} to any given exercise intensity (Iannetta et al., 2020). Lastly, to maintain a precise percentage of $HR_{max,}$ work rate would need to decrease over time, which may lead to an inadvertent shift across exercise domains, and thus a reduction in $\dot{V}O_2$ or metabolic stimulus.

2.1.2 The exercise intensity domains and thresholds approach

Independently of the methods that are used for exercise prescription, current lines of evidence highlight the relevance of understanding the metabolic disruptions induced by the intervention to better control the acute adjustments and chronic adaptations to endurance exercise (Inglis et al., 2024; Keir et al., 2018; Maturana, F.M. et al., 2021; Poole et al., 2012; Weatherwax, R.M. et al., 2018). This metabolic disruption can be framed within the exercise intensity domains model originally proposed by Whipp (1996). Briefly, this model separates exercise intensities as follows:

- Moderate intensity domain: below the GET.
- Heavy intensity domain: between the GET and the MMSS.
- Severe/extreme intensity domain: above the MMSS.

All of these intensities are separated by two precise physiological thresholds representing the boundaries at which these metabolic adjustments occur (Whipp et al 1996). Although the terminology surrounding these exercise intensity thresholds vary depending on the method of estimation, the terms most frequently used for the identification of the two exercise thresholds include the lactate threshold (LT) and GET for the first, and the respiratory compensation point (RCP), CP, MLSS, or MMSS for the second (Jones et al., 2019; Keir et al., 2018). A more in-depth description of these domains is as follows.

Moderate-Intensity Domain

This specific domain represents the range of work rates below the GET, reflecting metabolic rates that begin at rest to the upper limit of the domain (Whipp et al., 1996). Any work rate dictating the metabolic demands within this domain is considered as moderate-intensity exercise. The metabolic demands within the moderate domain are considered to be low, as exercise can be sustained for a very long period of time (~4 hrs) and reflects little to no $[La^-]_b$ accumulation, similar to resting levels, and $\dot{V}O_2$ responses that reach a steady state within ~2-3 minutes (Iannetta et al., 2020; Ozyener et al., 2001). This is because the demand for adenosine triphosphate (ATP) within the working muscle is met by the muscle oxidative glycolysis and fat oxidation, maintaining ATP upregulation (Keir et al., 2021). The activation of muscle glycolysis produces $[La^-]_b$ as an end product. Within the moderate domain, the rate of pyruvate production within the muscle is equal to the uptake and oxidation within the mitochondria, which ultimately leads to lower $[La^-]_b$.

Heavy-Intensity Domain

This domain represents the range of work rates above the GET up until the RCP (Whipp et al., 1996). Work rates influencing metabolic demands within this domain are considered as heavy-intensity exercises. Within the heavy domain, the $\dot{V}O_2$ responses are different compared to the moderate intensity domain because of the emergence of the $\dot{V}O_2$ slow component, which can increase the time to reach steady state exercise up to 15 minutes (Iannetta et al., 2020; Ozyener et al., 2001). With the increased metabolic stimulus in this domain, the rate of pyruvate production exceeds the rate of uptake and oxidation by the mitochondria, which leads to a greater increase in $[La^-]_b$ (Keir et al., 2022). Despite these greater increases in $[La^-]_b$, there are metabolic systems in place to “defend” the acidity balance within the muscle. These physiological buffering systems include the bicarbonate-CO_2 system, phosphates, and proteins (Calvo et al., 2021). The upper boundary of the heavy intensity domain is demarcated as the RCP or MMSS, which is the highest intensity of exercise that represents a steady state in both $\dot{V}O_2$ and $[La^-]_b$ responses (Iannetta, 2021).

Severe/Extreme-Intensity Domains

These domains represent the work above the MMSS, surpassing the achievability of steady state $\dot{V}O_2$ and $[La^-]_b$ responses (Iannetta et al., 2021). In the severe-intensity domain, the rate of ATP production from glycolysis and uptake increases over time and with it, $\dot{V}O_2$ responses and increases in metabolites such as hydrogen ions (H^+), and $[La^-]_b$ (Iannetta et al., 2021). Due to this increase in metabolic demand, pyruvate is produced at a high rate, exceeding not only the uptake and oxidation of the mitochondria, but also the metabolic systems (bicarbonate-CO_2 system, etc.) put in place to maintain acid-base balance within the muscle, making steady state unachievable (Keir et al., 2021; Poole et al., 2007). In the severe domain the slow component of $\dot{V}O_2$ is also more prominent, eventually pushing $\dot{V}O_2$ to $\dot{V}O_{2max}$ (Poole & Jones. 2012).

The extreme-intensity domain is essentially characterized by the inability to attain $\dot{V}O_{2max}$, the other responses (rapid increase in metabolites, $\dot{V}O_2$, $[La^-]_b$, etc.) are similar to those observed within the severe domain (Iannetta, Zhang et al., 2022; Poole & Jones. 2012). The noted inability to obtain $\dot{V}O_{2max}$ is due to the short amount of time spent within this domain (~1-2 min), creating a rapid onset of fatigue before $\dot{V}O_{2max}$ can be achieved (Poole & Jones. 2012). It is important to note that there is no distinct boundary separating the severe and extreme intensity domains, instead, they can be separated by work rate (Poole & Jones. 2012).

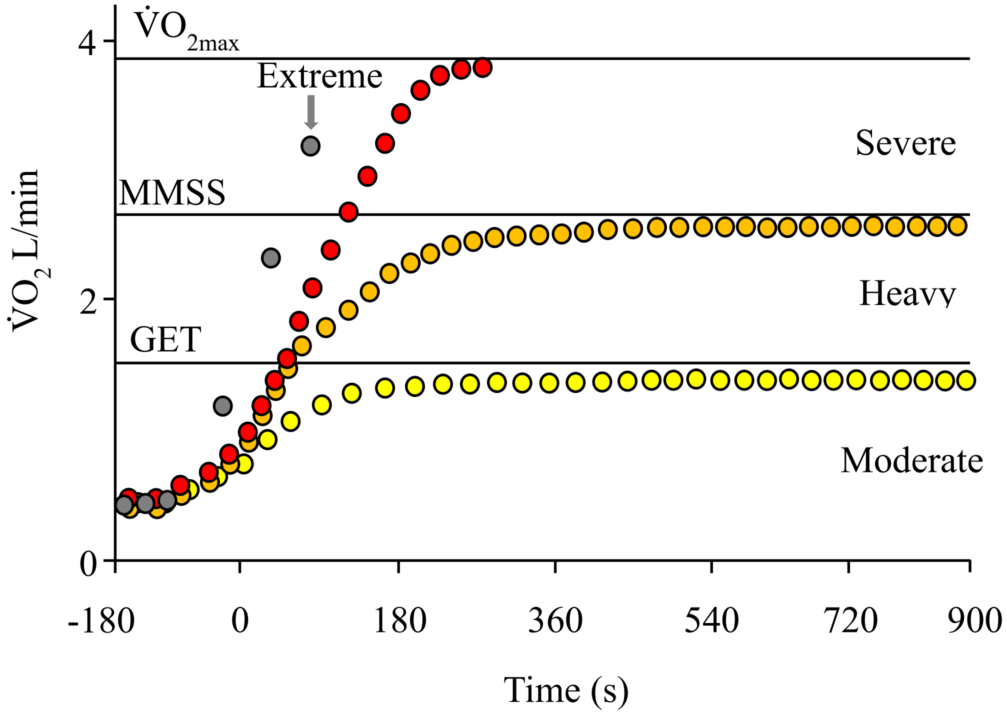

Figure 2.1.2. Graphic display of $\dot{V}O_2$ metabolic responses within the moderate-, heavy-, severe-, and extreme-intensity domains.

2.1.3 Comparing the percent of maximal responses to the thresholds approach

When it comes to prescribing exercise intensities, recent studies have highlighted the importance of being able to evaluate the MMSS (i.e., the boundary that separates heavy from severe domain intensity exercise) as a fundamental element to better understand the metabolic disruption generated by the stimulus, which then leads to better predicting the responses to exercise, and maximizing the beneficial adaptation outcomes of the intervention (Iannetta et al., 2021; Inglis et al., 2024; Maturana, F.M. et al., 2021). However, in all cases, it is important to note the methods that are utilized to determine this boundary offer a margin of error in its estimation.

In 2020, a study published by Iannetta et al. (2020) compared methods of exercise prescription based on fixed percentages of maximal values to other methods that more precisely categorize the metabolic disturbance of exercise. These other methods also consider the interindividual variations in the physiological responses to exercise to estimate the boundaries separating the moderate from the heavy and the heavy from the severe intensity domains. In the study, 100 individuals participated, 46 females and 56 males. Each participant underwent a cardiopulmonary ramp-incremental test to measure $\dot{V}O_{2max}$, PO_{peak}, HR_{max}, and the estimated LT (analogous to the GET). Participants also had their MLSS (i.e., a close representation of the MMSS) determined through 2-4 30-minute constant-work rate trials. The LT and MLSS values were used to differentiate the three domains of exercise intensity (moderate, heavy, and severe). The results of the study revealed that, in both sexes, there were very large ranges of percentage of maximal values at which the LT and MLSS were established. Considering all participants, the LT and MLSS occurred at, respectively, 45%-74%; 69%-96% of $\dot{V}O2_{max}$, 23%-57%; 44%-71% of PO_{peak}, and 60%-90%; 75%-97% of HR_{max} (Iannetta et al., 2020). These findings indicated that a very large interindividual variability exists in the percent of maximal/peak values at which exercise intensity thresholds occur and highlighted the limitations of using a fixed percent of maximal/peak responses as an effective tool to normalize exercise intensity between participants.

2.1.4 Critiquing the Percent of Maximal Responses Method

As indicated above, the results presented by Iannetta et al. (2020) indicated that the ranges of percentages that represent each exercise intensity domain can vary from person to person. Given that accountability for interindividual variations in physiological thresholds cannot be met by the fixed percentages of maximal/peak performance method, and that this approach for exercise prescription is still used in research and clinical settings today, the internal and external validity to evaluate the effects of exercise intensity on acute responses and chronic adaptations following an exercise training intervention in different studies is a cause for concern. For example, in a study by Di Pietro et al. (2005), moderate intensity was considered to be 65% of $\dot{V}O_{2max}$. These methods are also supported by Garber et al. (2011) in the American College of Sports Medicine guidelines for prescribing exercise. Considering the results by Iannetta et al. (2020), the methods proposed by Di Pietro et al. (2005) would not be appropriate to elicit a metabolic stress corresponding to moderate intensity domain exercise for some individuals, and it is quite likely to result in heavy intensity domain exercise in many of them. If the fixed percentage of maximal/peak responses method demonstrates a measurement bias between individuals given thresholds, it puts into question the generalizability of the results drawn from studies that aimed to evaluate the role of exercise intensity on any given outcome supposedly associated to that intensity.

Based on the information provided above, the exercise intensity thresholds and domains-based method provides a more adequate approach to control exercise intensity as it can effectively control the metabolic disruptions/stress generated by the proposed activity. This is especially important in connection to establishing the heavy to severe exercise intensity domain boundary, as it demarcates the limit between sustainable and unsustainable exercise (Iannetta et al., 2021, Keir et al., 2015). However, it is important to recognize that any method used to establish the true MMSS boundary, including the ones considered to be the gold-standard, reflect some degree of measurement error (Iannetta et al., 2021, Keir et al., 2015), and have different limitation/challenges for their implementation (e.g., use of a metabolic cart, multiple visits to the lab, highly demanding exercise, etc.) (Karsten et al., 2016) that can create potential validity and feasibility threats. Becoming more familiar with the advantages and limitations of each approach to approximate the exercise intensity associated with the MMSS can help in identifying the best methodological approach to determine the “critical intensity” of exercise depending on the circumstances affecting the evaluation.

2.2 Identifying the Heavy-Severe Exercise Intensity Boundary

As discussed earlier, the MMSS is the boundary representing the upper limit of exercise tolerance (Iannetta et al., 2021). This boundary distinguishes the heavy intensity domain from the severe intensity domain of exercise. There are different concepts that can be used to determine this boundary, including CP, MLSS, and RCP. Although controversy exists in relation to the optimal method to approximate MMSS (Keir et al., 2021; Mattioni Maturana et al., 2018), different lines of research indicate that both CP and MLSS represent good approximations to the MMSS (Keir et al., 2018; Mattioni Maturana et al., 2016). In fact, a recent study has indicated that CP and MLSS can be reconciled as, depending on the methodological approaches used for their determination, they can result in virtually identical outcomes (Iannetta et al., 2021).

2.2.1 Identifying the maximal lactate steady state

The MLSS is defined as the upper boundary of exercise where blood lactate production and utilization are equivalent (Billat et al., 2003). MLSS can be determined through the establishment of $[La^-]_b$ steady state, which is represented by a change of $\leq$ 1mmol-L at various time intervals during a 30-minute constant work rate test (Beneke, 2003). The method for evaluating MLSS is through blood sampling during these constant-power rides repeated on multiple occasions over a range of intensities (Svedahl & MacIntosh, 2003). The range of these given intensities should consider the intensity corresponding to MLSS as well as slightly above it. At any intensity above the GET and at MLSS, $[La^-]_b$ will increase initially before entering a steady state, whereas at intensities slightly above the MLSS an increase in $[La^-]_b$ followed by a steady rise throughout the constant-power ride will be evident (Svedahl & MacIntosh, 2003).

As mentioned above, MLSS can be identified during these constant-power rides through the establishment of $[La^-]_b$ steady state. Although what defines steady state $[La^-]_b$ is a source of debate, a change of ≤ 1mmol-L between 10-15 and 30 minutes during the constant work rate exercise is typically accepted as a valid approach (Iannetta et al., 2018; Iannetta et al., 2021; Keir et al., 2018). When considering these time intervals, prior studies have commonly used the final 20 minutes of a constant-power ride lasting at least 30 minutes as their method (Carter et al., 1999; Jones & Doust, 1998). However, a recent study has indicated that using 15-30 minutes results in MLSS results more closely approximating the true MMSS (Iannetta et al., 2021). Some benefits of MLSS testing include the fact that it includes a straightforward physiological measure of blood sampling that is carried out in real time with little equipment needed, and that it is an individualized measurement (Beneke, 2003; Svedahl & MacIntosh, 2003). However, limitations do exist. One of the main limitations of traditional MLSS testing within a study is that it requires multiple visits to the laboratory to get accurate values, and to some degree, invasive measures (Mattioni Maturana et al., 2016). The increment needed to accurately predict the MLSS has also not been established (Beneke, 2003; Svedahl & MacIntosh, 2003). Researchers will commonly use step increases of intensity around 4 to 5%, but these methods will differ between different lines of research. This is an important limitation to note as the precision of the estimate of MLSS is dependent on the magnitude of these intensity increases between visits.

2.2.2 Identifying the CP

As originally proposed by Monod H. and Scherrer J. (1965), CP is a theoretical concept that is based on the hyperbolic relationship between high-intensity exercise in the severe domain and exercise duration, with the asymptote of this relationship representing the highest intensity of exercise that can be sustained relying almost exclusively on oxidative metabolism without depletion of the curvature constant know as W prime (W') (Poole et al., 2016). The two-parameter model of this hyperbolic relationship (CP_{2HYP}) can be defined as PO-T_{lim} represented by the equation $T_{\mathrm{lim}} = W' / (PO – CP)$, with the t_{lim} representing time to task failure (TTF; duration a preestablished power output could be tolerated) and the constant W' representing the fixed amount of work that can be carried out above CP (Bishop, Jenkins & Howard, 1998; Iannetta et al., 2021).

CP testing offers a valuable estimate of the PO corresponding to the MMSS as well as the W' (Iannetta et al., 2021; Pool et al., 2006). Means of estimating the MMSS are very important when considering the prescription of exercise and utilizing the thresholds method highlighted above (Iannetta et al., 2020). Evaluating W' is also valuable in the realm of exercise prescription and performance as it can have useful implications on an individual's sustainable work capacity above CP (Bishop, Jenkins & Howard, 1998). CP is a solid method to identify this critical intensity of exercise associated to the MMSS, and various models and protocols can be considered when retrieving an estimate of CP (Jones & Doust, 1998; Mattioni Maturana et al., 2018).

CP is commonly determined by measuring work capacity where the muscle is taken through 4-5 trials at various PO ranging from 3–15 minutes (Bishop, Jenkins & Howard, 1998; Karsten et al., 2015; Mattioni Maturana et al., 2016; Monod H. & Scherrer J., 1965; Morton, 2006). These PO remain constant throughout the trials, and each is chosen specifically to engender a shorter or longer duration before task failure. These TTF trials are considered when affected muscles can no longer maintain the original output (Monod H. & Scherrer J., 1965). Aside from the traditional hyperbolic fitting method described above (CP_{2HYP}), a linear model can also be utilized (Bishop, Jenkins & Howard, 1998). This is possible when the product of PO and time (W) is presented as a function of TTF (T_{lim}). This two-parameter linear model can be defined as work-T_{lim} (CP_{lin}) represented by the equation $W = \text{CP}T_{lim} + W'$ *with* CP as the slope and W' as the y-intercept (Bishop, Jenkins & Howard, 1998; Iannetta et al., 2021). Alternatively, CP_{lin} can be linearized in a different form representing the linear relationship between power and inverse of time ($1/T_{\text{lim}}$) (Gaesser et al., 1995). Originally proposed by Whipp et al. (1982), this two-parameter linear model can be defined as PO-($1/T_{\text{lim}}$) ($\text{CP}_{1/T\text{lim}}$) represented by the equation $\text{PO} = W'(1/T_{\text{lim}}) + \text{CP}$ with W' as the slope and CP the y-intercept (Gaesser et al., 1995; Iannetta et al., 2021).

Aside from the traditional method used to derive CP (hyperbolic relationship of 3-5 TTF trials), other studies suggest that CP can be predicted through a more efficient 3-minute all out test ($\text{CP}_{3\text{MIN}}$) (Vanhatalo, Doust & Burnley, 2007). This test consists of a 3 min all out effort at a PO corresponding to halfway between $\dot{V}O_{2\text{peak}}$ and GET. $\text{CP}_{3\text{MIN}}$ was derived as the highest PO from the last 30 seconds of the trial that serves as a proxy of CP, with W' represented as the area under the curve of the fitted model (Vanhatalo, Doust & Burnley, 2007).

CP is a valuable metric for determining the highest intensity of exercise that corresponds to the MMSS (Iannetta et al., 2021; Poole., et al 2006). However, these various CP models have been utilized in numerous lines of work and the different estimates of CP can vary depending on the particular model used and duration of the TTF trials (Bishop, Jenkins & Howard, 1998; Bull et al., 2000; Gaesser et al., 1995; Morton, 2006; Muniz-Pumares et al., 2019). Some limitations regarding $\text{CP}_{2\text{HYP}}$ exist given that the model assumes infinite power as time approaches 0 and that at the point of total exhaustion the entirety of the W' has been depleted (Gaesser et al., 1995). To overcome these limitations Morton (1996) developed a modified hyperbolic model which included the maximal instantaneous power (P_{max}) (Gaesser et al., 1995). This three-parameter model can be defined as PO-T_{lim} (CP_{3HYP}) represented by the equation $t = (W' / PO – CP) + (W' / CP – P_{\max})$ (Gaesser et al., 1995; Iannetta et al., 2021).

Two important limitations of CP are: i) the requirement of the four to five TTF trials to be performed as efforts that are intended to result in maximal responses to exercise in order for an accurate prediction. If this prerequisite is omitted, the predictive value of the model is decreased, thus limiting the ability to precisely quantify the metabolic stress of the exercise; ii) the outcome from the model is accepted as the MMSS without physiological measures that allow for empirical demonstration that this was the case, which limits the applicability of the model (Keir et al., 2016). Is this case, it would be valuable to compare the outcomes of the CP model to models with a similar purpose such as MLSS, which takes physiological evaluations into account (Craig et al., 2015; Keir et al., 2018; Mattioni Maturana et al., 2016). Thus, shedding some light on the discrepancies and relationship between both modalities and providing further insight on the ability of these models to precisely identify the PO associated to the MMSS.

2.2.3 Testing the validity of CP methods by comparing MLSS values

In 2016, Mattioni Maturana et al., compared the different POs obtained from CP_{2HYP}, CP_{3MIN}, and MLSS. The study also measured the $\dot{V}O_2$ and $[La^-]_b$ at MLSS. In the study, 13 healthy individuals (4 females and 9 males) volunteered to participate. CP_{2HYP} was determined through the fitting of 5 TTF tests, $CP3_{MIN}$ was calculated as the mean PO during the last 30 seconds of a 3-minute all-out test, and MLSS was determined as the highest PO where the change in $[La^-]_b$ was $\leq$ 1mmol/L during the last 20 minutes of a 30-minute cycling test. The researchers also measured the limits of agreement (LOA) between the 3 measures using Bland & Altman plots.

The results from the study (Mattioni Maturana et al., 2016) indicated that the POs established by CP_{2HYP} (253 +/- 44 Watts (W)) and CP_{3MIN} (250 +/- 51 W) were greater than the POs obtained during the MLSS trials (233 +/- 41 W). Even though the mean POs associated with CP_{2HYP} and CP_{3MIN} did not differ significantly, the large LOA between the two CP measures (-39 to 31 W) and the inconsistency with the PO at MLSS (CP_{3MIN} and MLSS LOA: -29 to 62 W; CP_{2HYP} and MLSS LOA: -7 to 48 W) challenged the validity of CP concepts to estimate MMSS. MLSS also elicited the highest PO of stable $[La^-]_b$ and VO_2. It is important to mention that in the study only 1 participant was able to achieve stable $[La^-]_b$ when cycling at the PO established from CP_{2HYP}. CP_{2HYP} overestimated MLSS for the other participants leading to failure of reaching MMSS. Another interesting observation from that study was the large between-measure variability that existed between the two methods used for CP estimation (CP_{2HYP} and CP_{3MIN}). For example, even though the average PO at CP was similar between tests, the interindividual difference was large in several participants, which would likely result in different metabolic stress for exercise prescription at CP, which would be more evident in the participants who demonstrated the greatest differences in the estimation. In summary, even though the CP and MLSS concepts represent similar physiological thresholds, differences between the two models and the values they elicit can still exist as the study conducted by Mattioni Maturana et al., in 2016 demonstrated.

2.3. The Use of Ramp-Incremental Tests to Evaluate the PO at which MMSS Occurs

Although the MMSS corresponds with the $\dot{V}O_2$ at the RCP during a typical ramp-incremental test, establishing the PO at which the metabolic rate associated to the RCP threshold occurs during a ramp incremental is not possible without appropriate corrections taking place (Iannetta et al., 2020; Keir et al., 2021). This is because the relationship between $\dot{V}O_2$ versus PO identified from ramp exercise does not coincide with that observed during constant-load exercise. During ramp incremental exercise, the $\dot{V}O_2$ shifts out of alignment from PO immediately after ramp onset. This is related to the existence of the $\dot{V}O_2$ MRT, which is connected to the time delay between the increase in muscle $\dot{V}O_2$ and the expression of that increase in the cite of measurement (i.e., the mouth), plus the kinetics adjustment of $\dot{V}O_2$ (Iannetta et al., 2020; Keir et al., 2018; Ozyener et al., 2001). This range of misalignment remains constant below the LT, due to the linear increase in $\dot{V}O_2$ and PO within the moderate intensity domain of exercise. However, above LT where the $\dot{V}O_2$ kinetics slow down and the $\dot{V}O_2$ slow component starts to develop, there is a progressive increase in the functional gain ($\dot{V}O_2$/W). This misalignment in the $\dot{V}O_2$ -PO relationship that is evident during constant work rate exercise is not seen during ramp-incremental testing (Iannetta et al., 2020; Keir et al., 2018). This is because these $\dot{V}O_2$ kinetics responses are hidden during most ramp-incremental protocols, which make the $\dot{V}O_2$ -PO relationship appear as linear.

2.3.1 Can the PO associated to MLSS be derived from a ramp-incremental test?

A study conducted in 2018 by Iannetta and Fontana et al. sought out to predict the PO associated to MLSS from a single ramp-incremental (RI) test by developing a mathematical equation. The secondary goal of this study was also to test the validity and accuracy of the proposed equation.

At the onset of the study the authors took existing data from 4 independent research studies where MLSS was already established, to develop an equation that could predict the PO associated to the MLSS from a RI test to task failure. The known variables provided from the participants tested in these studies (n=60; 4 females and 56 males) included MLSS (in W and $\dot{V}O_2$), body mass, peak $\dot{V}O_2$ ($\dot{V}O_{2peak}$), GET, RCP, and PO_{peak}. As an important note, each of the tests performed by these participants were almost identical in the methods used to generate the said variables. Once the analysis was concluded and the MLSS PO equation was determined, the researchers then began the second phase of the study. A group of 29 participants (10 females and 19 males), different from the group of participants in the first phase, underwent testing to measure the validity of the generated model. Each participant completed a RI test to task failure, and 2-3 30-minute constant-power output rides to evaluate the predictive value of the equation. With the data from the RI test, the researchers applied the developed equation and the PO estimated to represent the MLSS was tested. The results showed that $MLSS_{pred}$ (predicted MLSS) was highly correlated with $MLSS_{obs}$ (observed MLSS) ($r = 0.93$; $p < 0.01$). Similarly, in the independent group $MLSS_{pred}$ was not different from $MLSS_{obs}$ (234 +/- 43 vs. 234 +/- 44 W; SEE 4.8 W; $r = 0.99$; $p < 0.01$; LOA = -9 to 11 W).

The study described above (Iannetta & Fontana et al., 2018) provided a tool that can be used to accurately estimate the PO associated with MLSS from a single RI test with high level of precision. Further, this test would allow for reducing the number of visits needed to verify the PO associated with MLSS, as the initial evaluation is likely to represent the true MLSS. The researchers concluded that the study results had a margin of error around 5%. Though this margin is present, it is important to mention that it is within the measurement of error that is typically associated with gold standard MLSS testing (+/- 10W), or even with evaluations of CP (Iannetta et al., 2022). Additionally, it is important to recognize that the MLSS estimation equation was derived from the results of a RI test with slopes of 25 $W \cdot min^{-1}$ for females and 30 $W \cdot min^{-1}$ for males. Though the ramp slope did not affect the developed model nor its validation during the analysis, the researchers suggest that the validity from using results from other RI test models remains unknown. Females were also somewhat underrepresented in the study, which could lead to issues in regard to the external validity of the study. Overall, the data from this study support the validity of the predictive MLSS equation and the researchers suggest using it as a time-efficient second option to the traditional MLSS testing method.

2.3.2 Different ramp protocols used in research and clinical settings and the MMSS

As discussed in a previous section, using ramp-incremental tests to accurately estimate the PO associated to MMSS (or to any constant-load exercise intensity above the GET) is challenging (Iannetta et al., 2020). This has resulted in the erroneous interpretation that the RCP is not a representation of the heavy-severe boundary. However, recent studies have used the coincidence of the $\dot{V}O_2$ at the RCP with the $\dot{V}O_2$ at the MMSS, combined with good understanding of $\dot{V}O_2$ kinetics and differences in ramp-incremental and constant-load exercise to develop strategies to solve the ramp to constant-load exercise dissociation in $\dot{V}O_2$ and PO (Iannetta et al., 2020).

Development of the "step-ramp-step" protocol

A study by Iannetta et al. (2020) was the first to propose the use of a "step-ramp-step" (SRS) protocol for determining the range of constant-load POs associated with any metabolic rate derived from ramp-incremental testing up to the MMSS with a single laboratory visit. In the study of Iannetta et al. (2020), 10 (5 females) recreationally trained individuals participated. The participants performed 4 to 5 five tests consisting of an SRS protocol and 3 to 4 constant-power trials. The SRS protocol included a moderate-intensity step transition (MOD; 2 min at 20 W followed by 6 min at 100 W), a ramp protocol (4 min baseline ride at 50 W followed by a 30 W·min^{-1} ramp to volitional exhaustion), followed by a heavy-intensity step transition (HVY;12 min ride at 50%-65% of PO$_{peak}$ from the ramp) after a period of recovery (30 min) following the ramp. The constant-power tests differed each visit, they all consisted of a 4 min ride at 50 W followed by either, i) a 12 min ride at the PO equal to the PO at HVY from the SRS, ii) a 30 min ride at the RCP PO elicited from the SRS, iii) a 30 min ride 5% above this PO, and iv) if needed a 30 min ride at 10% above SRS-elicited RCP PO. The study resulted in all participants completing 30 min of constant-power cycling at the SRS-elicited RCP reaching a steady state $\dot{V}O_2$ of 3176 ± 595 ml/min. This value did not differ ($p=0.80$) from the ramp-identified RCP of 3095 ± 570 ml/min and was very consistent within the participants. During the 30 min ride 5% above the SRS-elicited RCP, only 4 participants could not complete it and all, but 2 participants had non-steady state response in $[La^-]_b$ and $\dot{V}O_2$.

The results of the study suggest that the SRS protocol can accurately predict the PO associated with MMSS. Benefits of the SRS protocol include a single lab visit, assistance in exercise intensity prescription, and submaximal efforts before and after the ramp portion of the protocol; thus, making it more appropriate for various populations who have difficulty replicating efforts that are intended to result in maximal responses to exercise. The SRS has also been shown to work with smaller first constant power output steps, different ramp slopes, and to be able predict constant-load POs associated to any ramp-derived $\dot{V}O_2$ quite effectively (Iannetta et al., 2023; Mackie et al., 2023). With the results published by Iannetta et al. (2023) and Mackie et al. (2023) the SRS protocol proves to be suitable to further individualize the metabolic stimulus across a variety of exercise intensities as well as represent a solid adjustable framework to measure cardiorespiratory fitness in populations with different fitness levels and/or chronic conditions that require a less aggressive/more dynamic approach to implement the protocol. Overall, the SRS protocol holds a valuable role in exercise testing as it challenges current limitations of typical ramp protocols, which is something that has helped improve the validity of exercise testing and prescription altogether moving forward.

2.4 Concordance between Critical Power and the Maximal Lactate Steady state

Although both CP and MLSS are theoretically and practically good predictors of the MMSS, the consensus between CP and MLSS responses is inconsistent (Iannetta et al. 2021). Whereas some studies have shown good agreement between CP and MLSS (Keir et al., 2018), when measuring the concordance between CP and MLSS, a recent meta-analysis reported results which state that CP occurs at a greater PO (average 30 W higher) when compared to MLSS (Galán-Rioja et al., 2020). In 2021, a study completed by Iannetta et al. aimed to resolve the differences and to understand the inconsistency between values. The study focused on seeking out the relationship between CP and MLSS and their accordance with the MMSS when utilizing various models and criteria across the same group of participants.

In that study (Iannetta et al., 2021), 10 active male cyclists performed 7-10 exercise protocols to identify CP, MLSS, and MMSS. First, the participants completed a ramp-incremental test of 30 $W \cdot min^{-1}$, after a 4-min baseline ride at 50 W, to establish $\dot{V}O_{2max}$ and PO_{peak}. Secondly, the participants underwent 4 to 5 severe-intensity constant-power output trials to estimate CP. These tests began after a 4-minute baseline ride at 50 W, soon followed by an immediate increase to the preestablished PO (100%, 90%, 85%, and 75% of PO_{peak}, respectively). The purpose of these trials was to generate an optimal distribution of the duration at which these PO could be tolerated (T_{lim}), within the recommended duration of around 3 to 15 minutes (Bishop, Jenkins & Howard, 1998; Morton, 2006).

CP was then calculated using 4 different models, CP_{3HYP}, CP_{2HYP}, CP_{lin}, and $CP_{1/T\mathrm{lim}}$ (Iannetta et al., 2021). The model that yielded the smallest combined error of its parameters, termed $CP_{best\text{-}fit,}$ was used for the CP estimate. Finally, the participants performed 2 to 4 constant-power output tests to identify the highest submaximal rate of $\dot{V}O_2$ that can be sustained at steady state ($M\dot{V}O_{2ss}$). For the first constant-power output trial, the PO associated with the $CP_{best-fit}$ was used. Depending on whether certain thresholds (i.e., $\dot{V}O_2$) were stable or reached maximum, as well if participants found success or not completing the 30-minute constant-power output ride, the researchers either increased or decreased the PO by 10 W during the next visit. Using the same methods, further trials were executed until $M\dot{V}O_{2ss}$ measures were gathered.

MLSS was estimated from the same 30-minute constant-power output trials that were performed previously by the participants to determine $M\dot{V}O_{2ss}$ (Iannetta et al., 2021). When testing for MLSS, 5 different time intervals were considered to generate 5 separate values of MLSS, minutes 5-30 ($MLSS_{5-30}$), 10-30 ($MLSS_{10-30}$),15-30 ($MLSS_{15-30}$), 20-30 ($MLSS_{20-30}$), and 25-30 ($MLSS_{25-30}$). Establishment of $[La^-]_b$ steady state was represented by a change of $\leq$ 1 mmol/L between the given 5-time intervals. For most of the participants, the multiple constant-power output trials done to establish $M\dot{V}O_{2ss}$ were sufficient to accurately measure MLSS. However, for some participants, additional trials were needed (i.e. at 10 W higher or lower) depending on the $[La^-]_b$ responses, to meet the standard. The results from this study show that the relationship between CP and MLSS was the strongest when MLSS was measured as $MLSS_{15-30}$, $MLSS_{20-30}$, and $MLSS_{25-30}$. The PO identified at $M\dot{V}O_{2ss}$ was 243 +/- 43 W and of the many CP models and MLSS measurements, CP_{2HYP} (244 +/- 46 W), CP_{lin} (248 +/- 46 W), $MLSS_{15-30}$, and $MLSS_{20-30}$ (both 245 +/- 46 W), sequentially exhibited the greatest accordance with $M\dot{V}O_{2ss}$.

It can be gathered from the study conducted by Iannetta et al. (2021) that there were no statistical differences between the CP and MLSS measurements. However, it is important to mention that the consistency between the measurements varied greatly, depending on which model the values came from. It is also important to consider that all CP models and MLSS measurements used are subject to error and will present some level of inaccuracies when compared to $M\dot{V}O_{2ss}$.

Nevertheless, these results showed that the magnitude of concordance between CP and MLSS is dependent on the methods used. For example, estimating MLSS at later time intervals ($MLSS_{15\text{-}30}$, $MLSS_{20\text{-}30}$, $MLSS_{25\text{-}30}$) substantially improved the concordance when comparing these values of MLSS to the values of CP attained from the 3 two-parameter models. In summary, the researchers concluded that the differences from CP and MLSS are more so methodological than physiological, and that the previously reported outcomes of other studies, specifically the study done by Mattioni Maturana et al. in 2016 stating CP occurs at a higher PO than MLSS, are likely to be related to inaccuracies relating to CP calculations and/or MLSS testing methods (Iannetta et al., 2021). This idea is also supported by a previous study by Greco et al. (2021), where they measured the difference between CP and MLSS with untrained and trained participants, in which they showed similar differences between groups (untrained 38 W, trained 37 W). Importantly, the authors indicated that their CP methods may have been a strong limitation to their results, as they used only 3 CP trials ranging from 3 to 11 min, which is known to likely overestimate the CP outcome (Mattioni Maturana et al., 2018). It is also important to mention that the authors did not report the percentage difference between CP and MLSS within each group (untrained 19%, trained 11%), even when using a percentage delta value between MLSS trials (5%). This means that the absolute difference between CP and MLSS will most likely have a greater metabolic impact on the untrained compared to the trained participants. This percentage difference adds value to the idea of testing the accuracy of these models in untrained versus trained participants.

2.5 Utilizing CP and MLSS to Represent MMSS: Exploring each Methodological Approach

To estimate the MMSS, two different approaches are commonly used. On the one hand, the CP model, as discussed above, is based on the hyperbolic relationship between exercise intensity in the severe domain and exercise duration, with the asymptote of this relationship representing the highest intensity of exercise that can be sustained by oxidative metabolism (Poole et al. 2016). On the other hand, the MLSS protocol also represents the upper limit of exercise that can be sustained by aerobic resynthesis of energy, but it is based on physiological evaluations of $[La^-]_b$ (Craig et al. 2015). Both approaches provide an accurate approximation of the work rate at MMSS. As mentioned in a previous section, two important limitations of CP are: i) the requirement of the TTF trials to be performed and identified as highly demanding efforts in order for an accurate prediction, and ii) the outcome from the model is accepted as the MMSS without physiological measures stating this was the case. Both of these limitations affect the applicability of the model and should be explored further as they could create a gap in the outcomes from MLSS and CP (Keir et al. 2018). Given that the CP model relies on the ability of the participant to perform efforts that are intended to result in maximal responses to exercise, and that physiological verification of the CP outcome is not required, it is likely that untrained individuals who are inexperienced with testing are less likely to obtain CP measures that are a true representation of the MMSS compared to their well-trained counterparts who have more experience with testing, even when strict methods are applied.

2.6 Research Objectives

The primary objective of this thesis was to determine if the CP model was an appropriate tool to accurately estimate the PO associated to the MMSS in untrained individuals who are unaccustomed to performing efforts that are intended to result in maximal responses to exercise.

This was assessed by measuring and observing the dissociation between the POs corresponding to the CP and MMSS in untrained versus trained individuals.

2.7 Hypothesis

It was hypothesized that the untrained individuals would have a greater dissociation between the POs corresponding to their CP and MMSS versus their trained counterparts, due to their unfamiliarity with highly demanding exercise.

Chapter III: Methods

3.1. Participants

Twenty-four individuals (13 males and 11 females) participated in this study. Participants were divided into two groups: endurance trained and untrained. Sex and descriptive characteristics for each group are presented in Table 4.1. Inclusion criteria for training status was considered as per a previous study looking at similar groups (Rasica et al., 2022). Endurance trained participants were considered eligible for the study if they met the following inclusion criteria: $\geq$4 endurance activities/week and a $\dot{V}O_{2max} \geq$50 or 55 ml/kg/min, for females and males, respectively. Untrained participants were considered eligible for the study if they met the following inclusion criteria: not presently involved in any structured exercise training program and with a $\dot{V}O_{2max} \leq$40 or 45 ml/kg/min, for females and males, respectively. In addition to the inclusion criteria determining each participants category of eligibility (endurance trained or untrained), each participant had to meet the following inclusion criteria to be included in the study: successful completion of the Canadian Society of Exercise Physiology (CSEP) Get Active Questionnaire (GAQ) form; being between the ages of 18-45 years of age; being free of any known health problems including obesity, cardiovascular disease, metabolic disease, neurological disease, and arthritis, or any other conditions that may create a confounding bias within the study; taking any prescribed medication that may alter certain responses to exercise including cardiovascular, hemodynamic, or neurological, smoke or use tobacco products, and excessive alcohol consumption (females $\geq$7 drinks/week; males $\geq$15 drinks/week). Approval was obtained from the Conjoint Health Research Ethics Board at the University of Calgary to complete all components of this study (REB18-0916). Prior to all exercise, participants signed a written informed consent form.

3.2. Experimental Design

Figure 3.2 represents the protocol design. All participants were required to visit the laboratory 8-10 separate times, completing: i) a “step-ramp-step” (SRS) test to determine $\dot{V}O_{2max}$, PO_{peak}, and the PO estimated to represent the MMSS; ii) a series of 4-5 TTF trials at an average PO ranging from ~70%-90% of the PO_{peak} performed on separate days, in order to obtain TTF durations of ~3-15 min; iii) at least 2 (or as many as needed) 30-min constant work rate rides to establish MMSS. These 30-min constant work rate rides included continuous measurements of $\dot{V}O_2$ using a mixing chamber via a metabolic cart, and $[La^-]_b$ measurements at 5 min intervals via blood sampling collected into a capillary tube following a finger prick. Blood samples were analyzed immediately after the test using a laboratory lactate analyzer (Biosen C-Line; EKF Diagnostics, Barleben, Germany). For all visits, perceptual scale recordings (rating of perceived exertion (RPE), fatigue, dyspnea, and pain) were taken at 5 min intervals or immediately after exhaustion. The RPE measure was a 6-20 Borg scale ranging from very easy to maximal exhaustion and was used to measure the participants perceived effort at each point of recording. The fatigue, dyspnea, and pain scales were measured as 0-10 scaling from no fatigue, breathlessness, and pain to maximal fatigue, breathlessness, and pain and were used to assess participants whole body fatigue, difficulty of breathing, and leg pain, respectively, at the time of measurement. HR was measured and recorded continuously throughout the exercise trials. Stature was recorded using a stadiometer during the initial visit, and body mass was taken using a mechanical weight scale during each visit, prior to the exercise trial.

All visits were performed on an electromagnetically braked cycle ergometer (Veletron; RacerMate, Seattle, WA) in an environmentally controlled laboratory (temperature, 19-20 degrees Celsius; humidity, 50%-60%), with at least 48 hrs between each session, at a similar time of the day (±1 hr). The participants were asked to avoid vigorous exercise ≥ 24 hours before testing, the consumption of alcohol and caffeine ≥8 hours before testing, and food intake 2 hours before testing. Bicycle cadence was be determined through self-selection during the participants first visit (75-95 revolutions per minute [rpm]), and it was maintained consistently for the remainder of the study. The exercise trials were terminated when participants stopped cycling or when their cadence fell ≥10 rpm below their self-selected value for ≥10 seconds. Participants received verbal encouragement during the ramp portion of the SRS protocol as well as during the TTF trials and MMSS constant work rate rides. TTF trials were considered valid when participants reached ≥95% $\dot{V}O_{2max}$ (Black et al., 2017). Participants were blinded to work rate and time during the exercise trials.

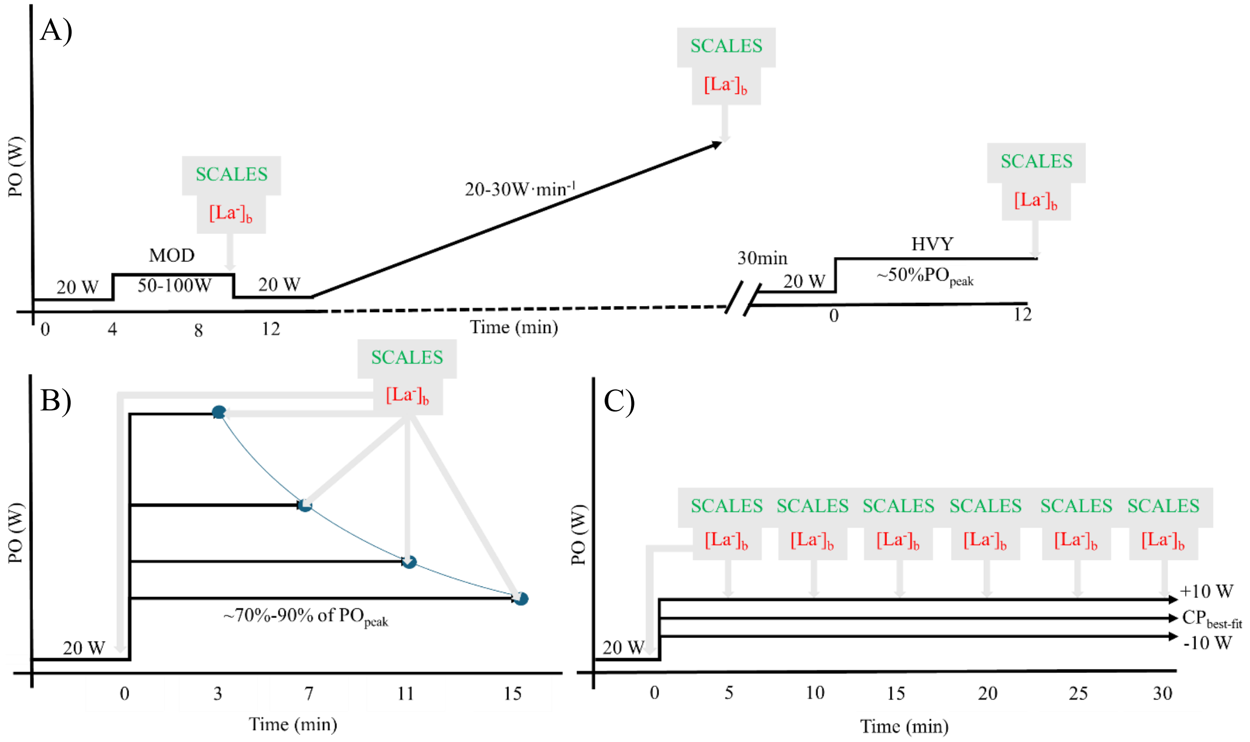

Figure 3.2. Schematic representation of the design of Visits #1 (top), #2-6, and #7-10 (bottom left to right). A, 4 min cycling warm-up followed by a 6 min MOD step transition into an RI test to task failure preceded by a 4 min warm-up, followed by ~30 min of rest into a 4 min warm-up with a 12 min HVY step transition, scales and $[La^-]_b$ taken during the last min of the MOD and HVY steps, and immediately post RI test. B, a 4 min warm-up followed by a severe TTF ride, scales and $[La^-]_b$ taken during the last min of the warm-up and immediately post TTF. C, a 4 min

warm-up followed by a 30 min constant-power ride, scales and $[La^-]_b$ taken during the last min of the warm-up and in 5 min increments from the onset of the ride until it is completed.

3.3. Procedures

3.3.1. Visit #1: SRS Protocol

On the first visit, after filling out the required documents (consent form and GAQ) and explaining all the physiological and perceptual measurements ($\dot{V}O_2$, heart rate (HR), $[La^-]_b$, Fatigue, Pain, RPE, and Dyspnea) as well as performing familiarization with these measurements, participants performed an SRS cycling protocol to establish, in addition to $\dot{V}O_{2max}$, exercise thresholds, and peak PO, the PO associated to MMSS (Iannetta, Inglis, Pogliaghi & Keir et al., 2020). The SRS protocol included: i) a baseline ride of 4 min at 20 W, followed by a moderate (MOD) constant power step transition of 6 min at 50-100 W (the PO selected varied based on the predicted fitness level of the participant to produce increases in $\dot{V}O_2$ measures that would maximize the signal to noise ratio while ensuring MOD responses); ii) a ramp incremental (RI) protocol that included a 4 min baseline ride at 20 W followed by a 20-30 W/min (20 W/min or 1 W every 3 for females; 30 W/min or 1 W every 2 for males) ramp to task failure as previously defined, iii) a 30 minute period of recovery followed by a baseline ride of 4 min at 20 W transitioning into a heavy (HVY) constant power step of 12 min at a PO set at 50%-65% of PO_{peak} achieved from the ramp. The HVY ride allowed for an estimation of the dissociation between the $\dot{V}O_2$ and PO relationship during the RI test and constant load test, thus attaining the estimated PO at MMSS (Iannetta, Inglis, Pogliaghi & Keir et al., 2020). At the end of the MOD step, RI test, and the end of the HVY step, $[La^-]_b$, Fatigue, Pain, RPE, and Dyspnea were all measured and recorded.

3.3.2. Visit #2-6: TTF Trials

During the next 4-5 visits, participants performed severe constant-PO TTF trials consisting of 4 min of baseline cycling at 20 W followed by an immediate increase in the PO to an intensity corresponding to (on average) 70%-90% of the participants PO_{peak} (Bishop, Jenkins & Howard, 1998; Iannetta et al., 2021). These rides were randomized and were intended to be performed at POs that were tolerated for ~3-15 min as recommended elsewhere (Bishop, Jenkins & Howard, 1998; Karsten et al., 2015; Mattioni Maturana et al., 2016; Monod H. & Scherrer J., 1965; Morton, 2006). Prior to the testing, participants were set-up for the physiological measurements and familiarized with the TTF protocol. A fifth trial was performed if the range of time achieved during one of the rides was suboptimal or if the standard errors (SEE) of CP and *W'* exceeded 5% and 10%, respectively (Black et al., 2017; Hill, 1993). CP was calculated through the ExPhysLab.com software website using the $CP_{2\text{-}hyp}$ model, the CP_{lin} model, and the $CP_{1/Tlim}$ model. The CP model that yielded the smallest combined SEE of its parameters was considered the one that produced the best fit ($CP_{best\text{-}fit}$). After base line and immediately after task failure, TTF, $[La^-]_b$, Fatigue, Pain, RPE, and Dyspnea were all measured and recorded.

3.3.3 Visit #7-10: Constant Work Rate Trials

On the last 2-3 visits, participants performed 2-3 30-min constant work rate tests to establish MMSS. Prior to the testing, participants were set-up for the physiological measurements. MMSS was defined as the highest PO associated with steady state VO_2 (<120 ml/min) and stable $[La^-]_b$ values (<1 mM) between the 15th and 30th min of the ride (Iannetta et al., 2021). The first test was set at the PO corresponding to $CP_{best\text{-}fit}$. Depending on whether the participants failed to complete the ride or to reach a stable $\dot{V}O_2$ and $[La^-]_b$ during the ride, or completed the 30 min ride with stable $\dot{V}O_2$ and $[La^-]_b$, the PO was increased or decreased by 10

W, respectively, until MMSS criteria was satisfied. At the end of the base line period and at every 5 min interval until test termination $[La^-]_b$, Fatigue, Pain, RPE, and Dyspnea were all measured and recorded.

3.4. Measurements

3.4.1 Ventilatory and gas exchange data

All ventilatory and gas exchange variables were collected via a metabolic cart (Quark, CPET; COSMED, Rome, Italy) using a mixing chamber measurement. The system consisted of a facemask connected to a two-way low-resistance T-shaped valve (2600 series; Hans Rudolph, Shawnee, KS), which was attached to the gas mixing chamber via a hose. A flow meter was attached to the mixing chamber along with low dead space turbine which measured expired flow rates. The gas mixture was automatically sampled at regular 10 s intervals to assess fractions of O_2 and carbon dioxide (CO_2). Before each test, the system was calibrated using a 3-L syringe and a gas-mixture of known concentrations (16.1% O_2; 5.12% CO_2; balanced nitrogen (N_2)). HR was recorded via blue tooth with a H10 Polar HR Monitor (Polar Electro, Inc., Kempele, Finland).

3.4.2 Blood lactate concentration

$[La^-]_b$ measurements were collected via a small finger prick from a lancet after cleaning the area with an alcohol swab. This initial step was followed by the collection of a 20 μL blood sample with a plastic capillary tube which was placed in an EKF prefilled safe lock plastic tube and mixed well before analysis using a laboratory lactate analyzer (Biosen C-Line; EKF Diagnostics, Barleben, Germany).

3.5. Data Analyses

3.5.1. Time data from the TTF trials

The time duration from the severe intensity TTF trials was taken and recorded from the conclusion of the baseline ride to the point at which the participant reached the necessary criteria for task failure, as described above.

3.5.2. Ventilatory and gas exchange data

After the conclusion of the RI test during the 30 min intermediate period, all the raw data files for the gas exchange data were analyzed via excel and Origin (Origin Lab, Northampton, MA). In this process, $\dot{V}_E$, $\dot{V}CO_2$, RER, $PetO_2$ and $PetCO_2$, $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$, were plotted against $\dot{V}O_2$ to identify the GET and RCP using the methods highlighted by Keir et al (2022). GET was estimated as the first point where $\dot{V}CO_2$ began to disproportionately increase to $\dot{V}O_2$, also known as the V-slope method (Beaver et al., 1986). Concurrently, this value was verified by the first breakpoint identified in the $\dot{V}_E/\dot{V}O_2$ and $PetO_2$ plots, as well as the point of stability in the $PetCO_2$ and $\dot{V}_E/\dot{V}CO_2$ plots. RCP was identified as the point at which $PetCO_2$ had a steep decline after a period of stability, concurrently to the second breakpoints in $\dot{V}_E$ and a steep increase in $\dot{V}_E/\dot{V}CO_2$ and $\dot{V}_E/\dot{V}O_2$. The mixing chamber gas exchange data were cleaned for each individual and interpolated into 1 s intervals. The different POs at GET and RCP were established via linear interpolation of the $\dot{V}O_2$-PO relationship (after accounting for the individual MRT), and after aligning the $\dot{V}O_2$ at the RCP with its steady state equivalent (Iannetta et al., 2019; Iannetta, Inglis, Pogliaghi et al., 2020). The $\dot{V}O_2$ and PO coordinates of GET and the HVY step transition identified the $\dot{V}O_2$-PO relationship in the heavy intensity domain of exercise. The extension of this relationship allowed for the estimate of the PO that is expected to elicit the $\dot{V}O_2$ at RCP.

During the RI test and constant power TTF visits, the highest mixing chamber measurements from a 20 s rolling average were considered maximal values (i.e., $\dot{V}O_{2max}$, $\dot{V}CO_{2max}$, HR_{max}, RER_{max}). The $\dot{V}O_2$ associated with the MMSS steady state criteria was computed from averaging the 2 min surrounding the 15th min (i.e., min 14-16) and the 2 min before the 30th min of the ride. If task failure was reached prior to the 30th min, $\dot{V}O_2$ values were taken during the last two min of the ride.

3.6. Statistical Analyses

Data are presented as mean ± standard deviation (SD). Sample size selection was based on previous studies measuring similar outcomes (Greco et al., 2012; Mattioni Maturana et al., 2016) and was deemed appropriate when statistical power for the main outcome measures was ≥80%. A mixed-model ANOVA was used to assess the difference in the POs associated to CP and MMSS in both untrained and trained individuals as well as the difference in CP and MMSS values between groups. A Shapiro-Wilk test was used to assess and confirm the normality of the data, and a Bonferroni correction was applied when necessary. Effect sizes were evaluated as small (d = 0.2), medium (d = 0.5), or large (d = 0.8) (Sullivan & Feinn, 2012). Paired t-tests were utilized to assess the differences in the CP and *W'* SEE as well as the total error (combined CP and *W'* SEE) between groups. Biases between CP estimates and MMSS values within each group were interpreted through Bland & Altman plots. Statistical significance was set at $\alpha < 0.05$ and statistical power was set at 80%. All statistical analyses were performed using SPSS version 29 (SPSS, IBM, Chicago, IL).

Chapter IV: Results

Table 4.1. displays the participant characteristics and the SRS test results at task failure. Whereas the untrained participants had a lower PO_{peak} and $\dot{V}O_{2max}$ than the trained, HR_{max}, maximal $[La^-]_b$ ($[La^-]_{bmax}$), maximal RPE, and anthropometric measurements (Stature, Body mass, and BMI) were not significantly different between groups. Participants body mass stayed consistent across all visits.

4.1. TTF test results in the untrained and trained groups.

For each of the TTF trials used to estimate CP in each group, Table 4.2 summarizes: the time duration, %RI-PO_{peak} at which the trials were performed, the peak $[La^-]_b$ ($[La^-]_{bpeak}$), RPE (RPE_{peak}), $\dot{V}O_2$ ($\dot{V}O_{2peak}$), and HR (HR_{peak}), as well as the percent of the RI-$\dot{V}O_{2max}$ and HR_{peak} values at which the responses occurred. There was no difference in the time duration between both groups from each TTF ride ($F = 0.026$, p = 0.87, $\eta^2 = 0.01$), but there was a significant difference in the duration between rides, without a group effect ($F = 505.41$, $p < 0.001$, $\eta^2 = 0.958$). The %RI-PO_{peak} decreased as the TTF increased ($F = 275.4$, $p < 0.001$, $\eta^2 = 0.926$), with a significantly greater %RI-PO_{peak} observed in the trained compared to the untrained group ($F = 7.1$, p = 0.014, $\eta^2 = 0.244$), which was consistent in each TTF ride (i.e., no interaction effect). The $[La^-]_{bpeak}$ and RPE_{peak} were not different between the rides ($F = 2.367$, p = 0.079, $\eta^2 = 0.097$, $F = 0.5$, p = 0.685, $\eta^2 = 0.022$), with no difference observed between groups ($F = 0.396$, p = 0.536, $\eta^2 = 0.018$, $F = 0.386$, p = 0.541, $\eta^2 = 0.017$). $\dot{V}O_{2peak}$ and %RI-$\dot{V}O_{2max}$ were both different between rides without a group effect ($F = 8.9$, $p < 0.001$, $\eta^2 = 0.288$, $F = 10.6$, $p < 0.001$., $\eta^2 = 0.325$). Significantly greater $\dot{V}O_{2peak}$ values were observed in the trained compared to the untrained groups across rides ($F = 13.9$, p = 0.001., $\eta^2 = 0.387$), while greater %RI-$\dot{V}O_{2max}$ values were observed in the untrained compared to the trained ($F = 10.4$, p = 0.004, $\eta^2 = 0.321$).

HR_{peak} and %RI-HR_{max} were both different between rides without a group effect ($F = 44.5$, $p < 0.001$, $\eta^2 = 0.669$, $F = 44.2$, $p < 0.001$, $\eta^2 = 0.668$). HR_{peak} was not different between groups across rides ($F = 1.2$, $p = 0.280$, $\eta^2 = 0.053$). %RI-HR_{max} was different between groups ($F = 5.8$, $p = 0.025$, $\eta^2 = 0.209$). Based on the results from the RI test, the $\dot{V}O_{2peak}$ responses during the TTF trials were above 95% of %$\dot{V}O_{2max}$ in both the untrained and trained groups for all the TTF rides.

4.2. MMSS, best-fit CP and *W′* in both untrained and trained groups.

Whereas the MMSS and CP were greater in the trained compared to the untrained participants, respectively ($t(22) = 5.21$, $p < 0.001$), $t(22) = 5.01$, $p < 0.001$), no significant differences between groups were observed for *W′* ($t(22) = 1.51$, $p = 0.145$) (see table 4.3). The SEE for CP, *W′*, and the total error were greater in the untrained compared to the trained participants ($t(22) = -2.658$, $p = 0.014$, $t(22) = -2.85$, $p = 0.009$, $t(22) = -2.942$, $p = 0.008$, respectively). The CP model R^2 values were not significantly different between groups ($U = 40$, $p = 0.065$, $r = -0.3772$). The smallest worthwhile change (SWC) for the difference between CP and MMSS was 2.1 W for the untrained group and 1.9 W for the trained group. Between the 3 best-fit models ($CP_{2\text{-hyp}}$, CP_{lin}, $CP_{1/T\text{lim}}$), the distribution of models selection was as follows: Untrained group, $CP_{2\text{-hyp}}$ was chosen 3 times, CP_{lin}, 1 time, and $CP_{1/T\text{lim}}$ 8 times; trained group, $CP_{2\text{-hyp}}$ was chosen 5 times, CP_{lin} 0 times, and $CP_{1/T\text{lim}}$ 7 times. No significant differences were observed between MMSS and the SRS derived MMSS (SRS-MMSS) values in both groups ($t(23) = 0.01$, $p = 0.99$).

4.3. CP and MMSS differences between the untrained and trained groups.

The PO associated to CP was significantly greater than that associated to MMSS in both untrained and trained individuals ($F = 13.2$, $p = 0.001$, $\eta^2 = 0.375$, effect size $d = 0.14$). No significant differences in CP and MMSS values were observed between the untrained and trained groups ($F = 0.01$, $p = 0.99$, $\eta^2 = 0.001$; statistical power = 99%). Figures 4.1 and 4.2 are the Bland & Altman plots representing the agreement between CP and MMSS in the untrained and trained groups, respectively. For both groups, the biases were significantly greater than 0 (untrained 7.5 W, $z = 2.57$; trained 7.5 W, $z = 2.95$). The 95% CI for the LOA were -13 to 28 W, and -11 to 26 W for untrained and trained, respectively.

Table 4.1. Participant Characteristics and the SRS test results at task failure.

Variable	Untrained Total (n=12)	Trained Total (n=12)	Independent Samples t-test
Age (yrs)	28.3±5.6	32.3±5.8	$p = 0.102$ $d = 0.70$
Stature (cm)	171.2±8.5	173.4±6.7	$p = 0.479$ $d = 0.29$
Body mass (kg)	69.7±11.4	69.9±9.4	$p = 0.962$ $d = 0.02$
BMI (kg/m^2)	23.7±2.9	23.2±2.2	$p = 0.620$ $d = - 0.21$
PO_{peak} (W)	254±61	348±58*	$p < 0.001$ $d = 1.57$
PO_{peak} ($W \cdot kg^{-1}$)	3.6±0.5	5.0±0.4*	$p < 0.001$ $d = 2.90$
$[La^-]_{bmax}$ (mM)	10.5±2.3	11.4±1.8	$p = 0.296$ $d = 0.45$
RPE (a.u.)	19±1	19±1	$p = 0.835$ $d = - 0.09$
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	2.74±0.68	3.81±0.62*	$p < 0.001$ $d = 1.65$
$\dot{V}O_{2max}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	38.9±4.7	54.4±3.4*	$p < 0.001$ $d = 3.77$
HR_{max} (bpm)	179±12	179±9	$p = 0.985$ $d = 0.01$

Data presented as mean±SD. *Significant difference from Untrained.

Table 4.2. TTF test results at task failure.

	TTF1		TTF2		TTF3		TTF4	
Variable	UT (n=12)	T (n=12)	UT (n=12)	T (n=12)	UT (n=12)	T (n=12)	UT (n=12)	T (n=12)
Duration (min)	3.6±0.8	3.5±0.7	6.4±1.1$^{\wedge}$	6.0±1.1$^{\wedge}$	9.6±1.2$^{\wedge+}$	9.7±1.7$^{\wedge+}$	14.5±1.3$^{\wedge+\$}$	14.7±1.7$^{\wedge+\$}$
% RI-PO$_{peak}$ (%)*	88±6	91±6	76±6$^{\wedge}$	81±4$^{\wedge}$	71±5$^{\wedge+}$	76±4$^{\wedge+}$	67±5$^{\wedge+\$}$	73±4$^{\wedge+\$}$
[La^{-}]$_{bpeak}$ (mM)	11.2±2.5	11.9±2.0	11.8±2.7	12.7±1.7	12.1±2.1	11.7±1.2	11.0±2.5	11.6±2.2
RPE$_{peak}$ (a.u.)	19±1	19±1	19±1	19±1	19±1	19±1	19±1	19±1
$\dot{V}O_{2peak}$ (L·min^{-1})*	2.71±0.66	3.64±0.59	2.77±0.65$^{\wedge}$	3.74±0.61$^{\wedge}$	2.81±0.70$^{\wedge+}$	3.78±0.66$^{\wedge+}$	2.69±0.67$^{\wedge+\$}$	3.71±0.58$^{\wedge+\$}$
% RI-$\dot{V}O_{2max}$ (%)*	99±3	96±2	102±3$^{\wedge}$	98±2$^{\wedge}$	103±3$^{\wedge+}$	99±2$^{\wedge+}$	99±4$^{\wedge+\$}$	97±4$^{\wedge+\$}$
HR$_{peak}$ (bpm)	171±12	167±8	178±10$^{\wedge}$	173±8$^{\wedge}$	180±11$^{\wedge+}$	175±7$^{\wedge+}$	180±12$^{\wedge+\$}$	178±6$^{\wedge+\$}$
% RI-HR$_{max}$ (%)*	96±4	94±3	100$^{\wedge}$	96±2$^{\wedge}$	101±2$^{\wedge+}$	98±2$^{\wedge+}$	100±3$^{\wedge+\$}$	99±3$^{\wedge+\$}$

Data presented as mean±SD. *Significant difference between groups. $^{\wedge}$Significant difference from TTF1. $^{+}$Significant difference from TTF2. $^{\$}$Significant difference from TTF3.

Table 4.3. MMSS values and the best-fit CP model values with the respective SEE and R^{2}.

	Untrained	Trained
SRS-MMSS	150±37	222±39*
MMSS (W)$^{\#}$	147±34	225±39*
CP (W)	155±39	233±37*
SEE (%)	1.9±1.0	0.9±0.8*
W′ (J)	14331±4884	17140±4197
SEE (%)	8.2±2.4	5.2±2.8*
Tot Error (%)	10.1±3.2	6.1±3.4*
SWC (W)	2.1	1.9
R^{2}	0.988-1.000	0.994-1.000
CP-MMSS Difference (%)	8.7±3.6	6.4±3.1

Data presented as range for R^{2} and mean±SD for the remaining parameter values. *Significant difference from Untrained. $^{\#}$Significant difference from CP.

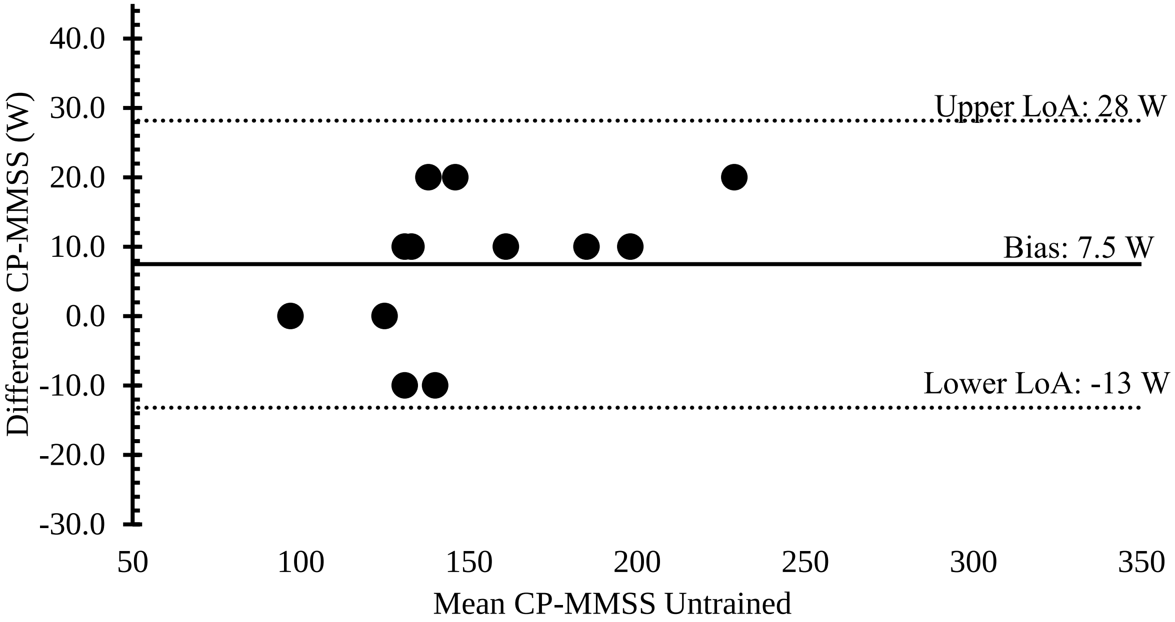

Figure 4.1. Bland Altman Plot Comparing the Difference in CP and MMSS in the untrained group with the CP versus MMSS mean.

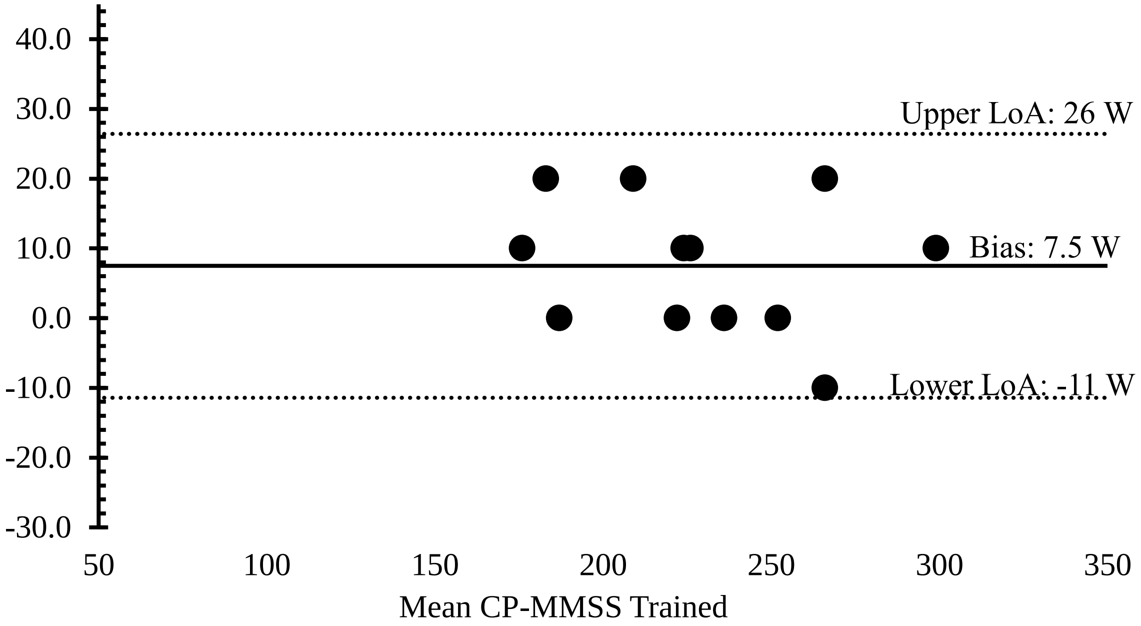

Figure 4.2. Bland Altman Plot Comparing the Difference in CP and MMSS in the trained group with the CP versus MMSS mean

Chapter V: Discussion

This study evaluated whether CP remained an appropriate method to accurately estimate the PO corresponding to the MMSS when testing untrained individuals who were unfamiliar with performing efforts that are intended to result in maximal responses to exercise. The main findings were that: *i)* despite a significant (albeit small) difference between CP and MMSS, the CP model provided a close approximation of the PO associated with the MMSS in both the untrained and trained participants; *ii)* the quality of the CP model was not meaningfully affected by training status, despite some minor differences between groups. This suggests that previous experience with participating in highly demanding efforts is not a key component of the quality of the prediction.

5.1. Differences in CP estimations between untrained and trained individuals

Performing efforts intended to approximate truly maximal responses to exercise during the TTF trials has been highlighted as an important component for obtaining accurate measures of CP (Keir et al. 2018). Thus, this need for performing maximal exhaustive tasks could have potential detrimental effects in the estimation of CP in some populations that are not used to these types of activities (Keir et al. 2018). Based on this idea, we hypothesized that the quality and the precision of the CP fit would be reduced in untrained compared to trained individuals. In opposition to this main hypothesis, the CP model provided a close approximation of the PO associated with MMSS in both the untrained and trained groups, despite the observed small but significant difference (~7 W) (see later for further discussion on this difference). This indicates that the CP model has good “flexibility” to provide an accurate estimate of the boundary separating the heavy from the severe intensity domains, regardless of training status or experience with participating in highly demanding efforts. Then, although the idea that performing trials that are as close as possible to being truly exhaustive holds true, what the present data indicate is that training status does not seem to have a meaningful impact in the CP estimation when recommended practices for accurate CP determination are followed (Black et al., 2017; Iannetta et al., 2021; Muniz-Pumares et al., 2019; Vanhatalo et al., 2007).

Despite the positive outcomes indicated above, some differences seemed to be more pronounced in the untrained compared to the trained participants. For example, despite the similar difference in the PO associated to CP and MMSS in the untrained compared to the trained participants, when looking at the percentage difference the untrained participants showed a greater dissociation (i.e., 8.6%), compared to the trained participants (6.4%). This is because the untrained participants had lower absolute values for the POs associated to CP and the MMSS compared to the trained individuals. This is a factor to consider as, even though our results indicate a similar absolute "error" in both conditions, the same absolute difference in PO would have greater impact from a metabolic disruption perspective in the untrained compared to the trained individuals. Importantly, this is not something that should be used as an argument against the model as, in fact, all models will have an inherent error of estimation that is virtually unavoidable. For example, the commonly used 10 W or 5% change in PO used for MLSS trials (Beneke, 2003; Fullerton et al., 2021; Iannetta et al., 2019) will determine a somewhat similar absolute error in the estimation (although only on one side of the probability). Similarly, the amplitude and duration of the steps will play a key role in the absolute error when estimating lactate thresholds for boundaries determination.

Another difference to highlight is that the SEE for CP and *W′*, and the total error (combined CP and *W′* SEE) were greater in the untrained compared to the trained participants. Though these values still fall into the acceptable margins of error for the CP and *W′*

measurements (Black et al., 2017; Iannetta et al., 2021), they were significantly different between groups. This could be because the untrained participants had poorer consistent performances during their TTF efforts compared to the trained participants, supporting one of the limitations indicated by Keir et al. (2018). Importantly these differences did not have a notable impact on the outcome values of CP. However, they suggest that more caution should be exercised when testing untrained individuals to limit these errors from sitting outside of the acceptable margins.

5.1.1. Differences in CP and MMSS estimations

In this study, the PO at CP was greater than the PO at the estimated MMSS, with this difference being present in both the untrained and trained groups. This is an important observation to consider when interpreting the error components in the analysis of the evaluation of the intensity associated to the heavy-severe domain boundary. On the one hand, the PO associated to the CP was unsustainable for 6 participants (i.e., they were not able to complete more than 12-26 min of exercise before task failure) or resulted in unstable $\dot{V}O_2$ and $[La^-]_b$ after 30 min in 9 participants, indicating that the intensity was above the MMSS. On the other hand, the MMSS measure included an error term of 9 W as the delta change between trials was 10 W. This means that, for example, for a participant being stable at 200 W but unstable at 210 W, the true MMSS was between 200 and 209 W. Then, the ~7 W difference observed between CP and MMSS also falls within the level of uncertainty of the MMSS measure. Although CP overestimated the MMSS in some participants, it is also true that the MMSS estimation might have underestimated the true MMSS in other participants. This becomes an important point of discussion as the idea of establishing a “gold-standard” for determination of the heavy-severe intensity domain boundary has become a topic of debate (Jones et al., 2019). Given the increased information on the relevance of precise identification of exercise intensity domains for accurate exercise prescription that maximizes the beneficial effects of the intervention (Iannetta et al., 2020; Inglis et al., 2024), we believe that it is important to highlight the effectiveness of different approaches to closely approximate the heavy-severe boundary instead of trying to pursue the "illusion" of a gold-standard.

In connection to these ideas, it is important to emphasize that following strict standards for the determination of the PO associated with the MMSS is always important, not only when estimating CP, but also when using MLSS or other approaches such as the SRS protocol. In fact, it is quite likely that the inconsistent responses often observed when evaluating the PO at CP, MLSS, or even the RCP (Galàn-Rioja et al., 2020; Greco et al., 2012; Mattioni Maturana et al., 2016; Muniz-Pumares et al., 2019; Pringle & Jones, 2002) are largely related to methodological considerations rather than to the physiological bases underlying these different outcomes to approximate the MMSS (Iannetta et al., 2021). For example, the dissociation between the PO at CP and the PO at the RCP from incremental testing highlighted in a review by Galàn-Rioja et al. (2020) is not as apparent if the dynamics of $\dot{V}O_2$ during constant work rate compared to ramp incremental exercise are considered (Iannetta et al., 2020; Keir et al., 2021). It has been extensively demonstrated that the metabolic rate at the RCP represents the metabolic rate at the MMSS, and that appropriate corrections using the SRS protocol (Iannetta et al., 2020), or even predictive equations (Caen et al., 2020; Iannetta & Fontana et al., 2018) are sufficient to approximate the PO at MMSS, with a measurement error that is not different from that obtained during CP testing (Iannetta et al., 2020). In relation to the dissociation between the PO associated to CP and MLSS, it has been shown that the discrepancies can be virtually abolished when a time window that allows for a more complete expression of the $[La^-]_b$ kinetics is used for MLSS determination (i.e., considering the Δ in $[La^-]_b$ from min 15-30 instead of min 10-30) (Iannetta et al., 2021).

5.2. Summary of the Interpreted Results

In summary, this study evaluated CP in untrained and trained participants to determine whether this model was appropriate to accurately estimate the PO corresponding to the MMSS in both groups, despite the potential limitations with performing efforts intended to result in maximal exercise in the untrained individuals. Despite a small (albeit significant) difference in the PO associated with CP compared to MMSS, the CP provided a close estimation of MMSS that was not affected by the training status of the participants. Beyond the potential arguments about what model should be selected, CP can be utilized in untrained participants despite their inexperience with highly demanding exercise efforts, at least when strict testing conditions are followed.

Chapter VI: Conclusions

The objective of this thesis was to determine whether the CP model was able to provide an accurate estimation of the PO associated to the MMSS in untrained participants who were unaccustomed and inexperienced with participating in highly demanding efforts intended to result in maximal performance exercise to volitional exhaustion.

The findings presented in Chapters IV and V of this thesis demonstrated that the CP model provides a close approximation of the PO associated to the MMSS in both trained and untrained participants and that the overall quality of the prediction model was not generally affected by training status, despite some minor differences between groups. This suggests that previous experience with highly demanding efforts is not a key component of the quality of the evaluation.

6.1. Limitations and Methodological Considerations

There are some potential imitations and experimental considerations to take into account. These include: *i)* typical measurement error associated with the prediction models; *ii)* the duration and order in which the CP and MMSS trials were performed; *iii)* the ability of the participants, especially the untrained, to achieve their highest level of performance during TTF trials.

Despite following these strict methods, the evaluation of the constructs in this study were prone to some measurement error and limitations when estimating the boundary between the heavy- and severe-intensity boundary. Although different approaches can be used to assess CP and MMSS (Bishop, Jenkins & Howard, 1998; Bull et al., 2000; Gaesser et al., 1995; Iannetta et al., 2021; Keir et al., 2021; Mattioni Maturana et al., 2018; Morton, 2006; Muniz-Pumares et al., 2019; Vanhatalo, Jones & Burnley, 2011), the literature supports our choices and justifies our reasoning behind them (Black et al., 2017; Iannetta et al., 2021; Muniz-Pumares et al., 2019; Vanhatalo et al., 2007).

Another limitation in this study would be the duration and order in which the CP and MMSS trials were conducted. Each participant completed the CP TTF trials prior to the MMSS trials as this was part of our study design (in order to start the first MMSS trial at the CP elicited PO), but because these trials were performed over 2-3 weeks some may argue that the CP trials could cause a training effect in the untrained participants prior to the MMSS trials. This would be more likely to occur in the untrained participants, which could result in increasing their level of fitness and affecting the nature and quality of the model predictions. However, considering the short duration of the TTF trials and the recovery period in between them, it's quite unlikely that a meaningful training effect occurred, especially in regard to performance outcomes. This was also considered during the MMSS trials, and sufficient time was given between them in order to avoid this effect. The order of which trials were completed first could have been randomized by starting some participants at the SRS derived MMSS PO for the MMSS trials and then completing the CP TTF trials afterwards, but using the SRS PO could cause limitations as well as it is also a prediction. In the end we just decided to use the more established model as a valid/accepted evaluation of CP was needed. In nature, given the long duration of the study, other events could also affect the outcomes (sickness, unexpected life interruptions, etc.). Nevertheless, methods were kept the same for each participant and limitations will always exist, regardless of which set of trials commenced first.

A concern from the onset of the study was the ability of the participants, especially the untrained, to offer efforts that closely approximate maximal responses to exercise. To make sure this limitation was controlled for, strong communication and verbal encouragement was delivered to all participants prior to and during the TTF trials.

6.2. Future Directions

Given the relevance to apply appropriate exercise prescription to maximize the beneficial effects of the intervention (Iannetta et al., 2020; Inglis et al., 2024), exploring whether the CP model would work in clinical populations is important. This study showed that healthy but untrained participants showed strong fits for CP, which closely approximated MMSS. However, it is unclear whether the CP model will still work in some populations that might be less willing or capable to participate in highly demanding performance exercise (e.g., chronic obstructive pulmonary disease (COPD) or cardiac rehab patients). Given the practical complexity of the CP model, pertaining to the number of visits required for an accurate estimation, individuals outside of a laboratory setting may not be as interested in utilizing the model. However, CP values established using TT efforts in a field setting have a good level of agreement with laboratory determined CP values (Karsten et al. 2015). This leads to the practical idea of potentially fitting the testing into training sessions for individuals when using the model in a field setting, specifically trained individuals, creating a less cumbersome method of measuring CP.

6.3. Final Remarks

In conclusion, this study demonstrated that the CP model can provide a close approximation of the PO associated with the MMSS in untrained and trained individuals, with training status not being a meaningful factor, despite some minor differences between groups. These findings suggest that when strict CP testing conditions are met, previous experience with highly demanding exercise is not a key component of the quality of the prediction.

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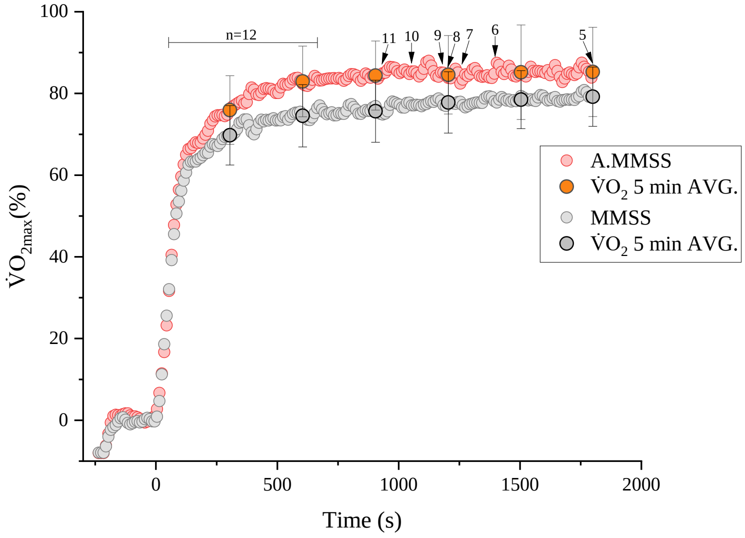
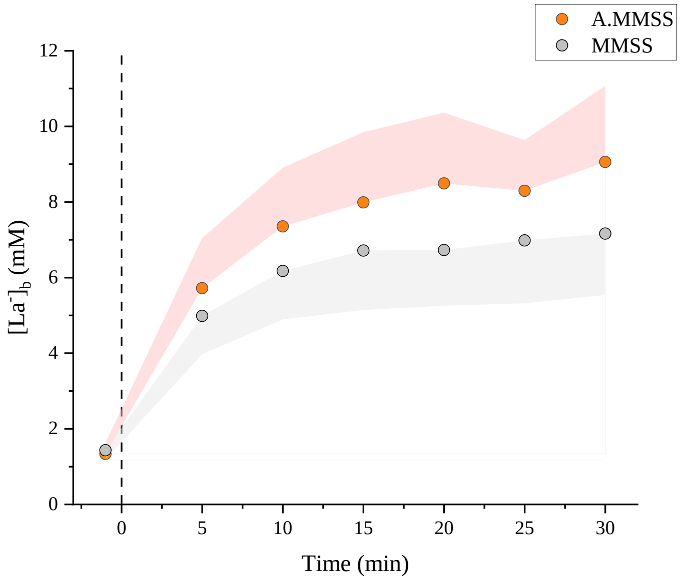
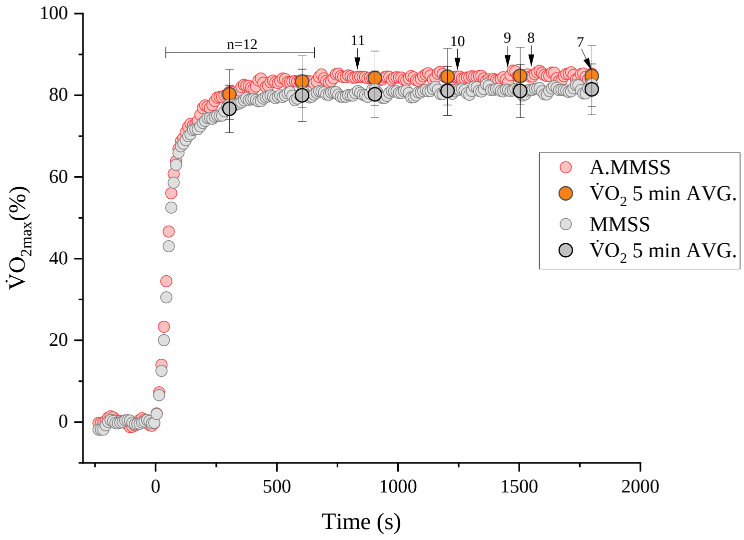
Appendix A: Supplementary Figures

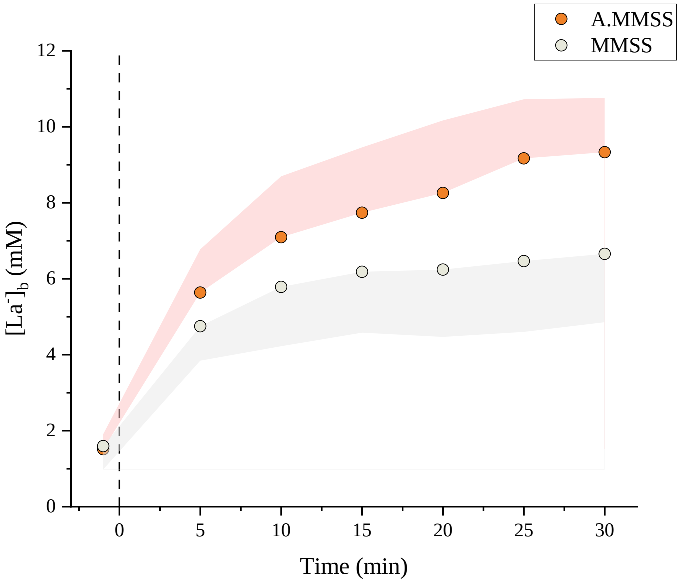


Supplementary Figure 1. $\dot{V}O_2$ responses at and above MMSS in untrained participants. Numbers displayed above the individual data points represent the number of participants from which the specific point was obtained.



Supplementary Figure 2. $[La^-]_b$ responses at and above MMSS in untrained participants.





Supplementary Figure 3. $\dot{V}O_2$ responses at and above MMSS in trained participants. Numbers displayed above the individual data points represent the number of participants from which the specific point was obtained.

Supplementary Figure 4. $[La^-]_b$ responses at and above MMSS in trained participants.