Impact of High Intensity Interval Training Versus Traditional Moderate Intensity Continuous Training on Critical Power and the Power-Duration Relationship

Jessica Rose Collins
Brigham Young University

Follow this and additional works at: https://scholarsarchive.byu.edu/etd

Part of the Life Sciences Commons

BYU ScholarsArchive Citation

This Thesis is brought to you for free and open access by BYU ScholarsArchive. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of BYU ScholarsArchive. For more information, please contact ellen_amatangelo@byu.edu.
Impact of High Intensity Interval Training Versus Traditional Moderate Intensity Continuous Training on Critical Power and the Power-Duration Relationship

Jessica Rose Collins

A thesis submitted to the faculty of Brigham Young University in partial fulfillment of the requirements for the degree of Master of Science

Jayson R. Gifford, Chair
Pat Vehrs
Ty Hopkins
Mandy Christensen

Department of Exercise Sciences
Brigham Young University

Copyright © 2021 Jessica Rose Collins
All Rights Reserved
ABSTRACT

Impact of High Intensity Interval Training Versus Traditional Moderate Intensity Continuous Training on Critical Power and the Power-Duration Relationship

Jessica Rose Collins
Department of Exercise Sciences, BYU
Master of Science

Critical Power (CP) is the greatest power that a person can sustain for prolonged periods of time while maintaining steady state conditions. Work-prime (W’) is the amount of work that can be tolerated when exercising in non-steady-state conditions above CP. A person’s CP and W’ strongly influence the metabolic response and tolerance to exercise.

PURPOSE: Compare the effect of equal amounts of moderate intensity continuous training (MICT) and high intensity interval training (HIIT) on CP and W’.

METHODS: Twenty-two (10 female) untrained, young (26.4 ± 0.9 years) adults completed 8 weeks of cycling training (40 min, 3 × per week) administered as either MICT cycling (44% max work rate achieved during a maximal graded exercise test; GXTmax) or HITT cycling (4 bouts at 80% GXTmax for 4 min with recovery intervals between). Cycling VO₂max, CP, W’ and Anaerobic Capacity (i.e., Wingate) were determined before and after training. Specifically, CP was assessed with the work-over-time method derived from 4–5 constant-power tests to exhaustion.

RESULTS: MICT (n = 11) and HIIT (n = 11) groups completed the same amount of work over the course of the training (P = 0.76). CP significantly increased in both groups, but to a greater extent in the HIIT group (MICT: 15.7 ± 3.1% vs. HIIT: 27.5 ± 4.3%; P = 0.04). The work that could be performed above CP (i.e., W’) was not significantly impacted by training (p = 0.76). VO₂max significantly increased in both groups (P < 0.01), and the magnitude tended to be greater in the HIIT group (MICT: 8.3 ± 2% vs. HIIT: 14 ± 2.6%; P = 0.09). Interestingly, the training-induced change in CP was not significantly related to the training-induced change in VO₂max. The training-induced increase in CP exhibited a positive curvilinear relationship with the training intensity, expressed as a percentage of the initial CP, with those performing the same workout at a greater percentage of CP exhibiting greater training-induced increases in CP ($R^2 = 0.49$, P < 0.01).

CONCLUSION: HIIT elicits approximately twice the increase in CP than an equal amount of MICT in untrained young adults. Moreover, the magnitude of increase in CP is strongly related to the intensity of the exercise, relative to CP, even when exercising at the same percentage of GXTmax. Thus, exercise may be more effectively prescribed relative to CP, rather than VO₂max or GXTmax.

Keywords: critical power; endurance; exercise domains; exercise programming; power-duration relationship
ACKNOWLEDGEMENTS

I want to thank so many people who helped make all this possible! My advisor, Dr. Gifford, helped me narrow and formulate my ideas over a thousand brainstorming sessions; and even more, he inspired me always to keep learning and reminded me that I am often capable of more than I think. I also want to thank my husband, Scott Collins. Thank you for always encouraging me to pursue my dreams, keeping me sane while I pursue them, and for dreaming with me. I also want to thank the many undergraduate students who helped with so many different aspects of this huge project. Specifically, I want to thank Meagan Proffit and Abi Dorff for helping kick this project off in the beginning, and Megan Sherman and Olivia Leach for helping keep this project moving forward, even amid the COVID-19 pandemic. Thank you for the countless hours of running tests in the lab, brainstorming sessions of potential side projects, and for your friendship. Thank you to my committee for all your support and advice and to all the participants of this study for your dedication. Thank you to all of my family and friends for your excitement and support over the last two years. Every one of you have made this experience perfect.
TABLE OF CONTENTS

TITLE PAGE ................................................................................................................................... i

ABSTRACT .................................................................................................................................... ii

ACKNOWLEDGEMENTS ........................................................................................................... iii

TABLE OF CONTENTS ............................................................................................................... iv

LIST OF FIGURES ....................................................................................................................... vi

LIST OF TABLES ........................................................................................................................ vii

Introduction ..................................................................................................................................... 1

Methods........................................................................................................................................... 4

Subjects ..................................................................................................................................... 4

Procedures ..................................................................................................................................... 4

Protocol #1: Proof of Concept of CP as a Steady-State and Sustainability Threshold ...... 5

Protocol #2: Comparison of the Acute Metabolic Demands of the MICT and HIIT

Workouts ............................................................................................................................................... 5

Protocol #3: Impact of 8 Weeks of MICT or HIIT on CP and Exercise Tolerance ......... 6

Assessment of Body Composition with DEXA Scan ................................................................. 7

Assessment of VO₂max and GXTmax ................................................................................................. 7

Verification of VO₂max .................................................................................................................. 8

Assessment of CP and W’ ......................................................................................................... 9

Assessment of Wingate Max and Average Power ................................................................. 10

Statistical Analysis .................................................................................................................. 10

Results ........................................................................................................................................... 11

Protocol #1: Proof of Concept of CP as a Steady-State and Sustainability Threshold ......... 11
Protocol #2: Comparison of the Acute Metabolic Demands of the MICT and HIIT Workouts .............................................................. 12

Protocol #3: Impact of 8 Weeks of MICT or HIIT on CP and Exercise Tolerance ............. 13

MICT and HIIT Group Comparisons—Retention and Total Work Completed ............. 13
Impact of MICT and HIIT on Body Composition ...................................................... 13
Impact of MICT and HIIT on CP ........................................................................... 14
Impact of MICT and HIIT on W’ ....................................................................... 14
Impact of MICT and HIIT on Endurance (Time-to-Task Failure) ......................... 15
Impact of MICT and HIIT on \( \dot{V}O_2 \text{max} \) ....................................................... 15
Impact of MICT and HIIT on GXTmax ................................................................. 16
Impact of MICT and HIIT on WINmax and WINavg ...................................... 17
Relationship Between Training-Induced Improvements in Endurance and Physiological Variables ........................................................................................................ 18
Relationships Between CP and Other Physiological Variables .............................. 18

Discussion .............................................................................................................. 20

Critical Power as a Maximal Metabolic Steady State: Proof of Concept .................. 20
Do HIIT and MICT Training Impact CP, W’ and Endurance? ............................... 21
Why Did Endurance Increase? ............................................................................. 23
How and Why Did CP and W’ Increase? .............................................................. 24
How Do CP and W’ Relate to Endurance? ............................................................ 25

Practical Application: Training Prescribed by CP .............................................. 26

Conclusions .......................................................................................................... 28

References ............................................................................................................. 30
LIST OF FIGURES

Figure 1: Proof of Concept of CP as a Threshold for Steady-State Conditions ........................... 36
Figure 2: Comparison of the Acute Metabolic Demands of MICT and HIIT Workouts ............... 37
Figure 3: Impact of 8 Weeks of MICT or 8 Weeks of HIIT on CP, W’, and Endurance .......... 38
Figure 4: Relationship Between Training-Induced Changes in Physiological Variables and Endurance ..................................................................................................................................... 39
Figure 5: Relationship Between Training-Induced Changes in \( \dot{V}O_2\text{max} \) and CP and W’ ........ 40
Figure 6: Relationship Between Training Intensity and the Training-Induced Increase in CP .... 41
LIST OF TABLES

Table 1: Metabolic and Caloric Differences Between MICT and HIIT Workouts ................. 42
Table 2: Subject Characteristics Within MICT and HIIT Groups at Baseline ..................... 43
**Introduction**

One’s ability to perform endurance exercise is influenced by multiple factors, including an individual’s maximum rate of oxygen consumption ($\dot{V}O_2\text{max}$), critical power (CP) and work-prime ($W^*$), lactate threshold (LT), cardiovascular oxygen delivery (1, 2) and anaerobic capacity (3–5). Research indicates that training methods can greatly influence the adaptations to the aforementioned performance factors (6–8), consequently improving performance (3, 4, 9). Among these physiological factors, $\dot{V}O_2\text{max}$ is often considered the most important factor influencing endurance performance (1, 6, 10), and consequently, a plethora of studies have researched how to improve one’s $\dot{V}O_2\text{max}$ to improve performance. Studies, such as by Helgerud et al. (6), Wisloff et al. (7), and Ocel et al. (8), have examined the popular endurance programs, moderate intensity continuous training (MICT) and high intensity interval training (HIIT), and their effects on $\dot{V}O_2\text{max}$. MICT is generally described as a prolonged exercise at one given moderate intensity, and HIIT is described as alternating periods of high intensity exercise (1–4 min) and periods of much lower intensity exercise.

Helgerud et al. compared the effects of four different levels of training intensities (based on an individual’s heart rate max (HRmax)) on $\dot{V}O_2\text{max}$ (6). Male subjects, who were currently endurance training, were randomly assigned to one of 4 groups:

1) long slow distance (70% HRmax); 2) lactate threshold (85% HRmax); 3) 15/15 interval training (15 s of running at 90–95% HRmax followed by 15 s of active resting at 70% HRmax); and 4) 4 × 4 min of interval running (4 min of running at 90–95% HRmax followed by 3 min of active resting at 70% HRmax) (6).

After 8 weeks of training, they found that, even though subjects performed the same amount of work in each of these programs, the higher intensity interval training groups (Groups 3 and 4)
experienced much greater increases in $\dot{V}O_2\text{max}$ (5.5% and 7.2%, respectively) than the moderate intensity training groups (Groups 1 and 2), which saw no significant changes in $\dot{V}O_2\text{max}$ from pre- to posttraining (6). Overall, such training studies have concluded that HIIT improves $\dot{V}O_2\text{max}$ to a greater degree than MICT (6–8, 11, 12), which is consistent with the previous explanations of the different physiological responses between the different exercise domains (13–15). However, these studies have not explored the relative impact of these programs on other factors, such as CP and $W'$.

CP is an important fatigue threshold (commonly distinguished as the threshold between the heavy and severe exercise intensity domains (13, 16)) with power outputs just above CP generating fatigue and leading to task failure exponentially faster than power outputs just below CP (9, 16). By definition, CP is the highest power output that elicits steady state (i.e., compensable) conditions, with $\dot{V}O_2$, muscle pH and muscle phosphocreatine levels all stabilizing below CP. In contrast, exercise above CP rapidly exhausts phosphocreatine stores needed to perform the exercise and inexorably produces fatigue-inducing metabolites that progress towards maximal tolerable levels, thereby eliciting $\dot{V}O_2\text{max}$ and task failure (9, 14–17). The amount of work, or more specifically the amount of metabolic disturbance, that can be performed and tolerated above CP before maximal tolerable conditions are reached and task failure occurs is a fixed amount referred to as $W'$ (16, 18). Thus, exercising at intensities below the CP threshold minimizes the accumulation of fatigue-inducing metabolites thereby allowing an individual to exercise for longer periods of time than when exercising at intensities above CP (16, 17, 19). Importantly, where CP occurs in relation to $\dot{V}O_2\text{max}$ varies from person to person, such that individuals with the same $\dot{V}O_2\text{max}$ can exhibit very different levels of endurance at the same
power output (16, 20, 21). Consequently, a person’s CP can be even more influential on endurance performance than VO2max (16, 20, 21).

As previously mentioned, MICT and HIIT are popular endurance training programs, but their effects on CP and W’ have not been thoroughly investigated (13, 22, 23). In the only study (to our knowledge) that investigated the effects of MICT and HIIT on CP, Gaesser et al. found that after 6 weeks the MICT group (exercising for 40 min at 50% VO2peak) increased CP by 13.4%, and the HIIT group (performing 10 high intensity intervals for 2 min each at VO2peak) increased by 15% (23). Although there were no significant differences between groups (23). However, this study included a small sample (n = 11) and all were relatively endurance trained males (23). They also did not match the MICT and HIIT groups for work completed. Therefore, these findings are inconclusive without further comparisons in females, untrained subjects, and when matching the groups for work completed.

Consequently, the purposes of this study were to investigate the effects of 8 weeks of HIIT and MICT endurance training on CP and W’ in untrained males and females and to determine how changes in CP and W’ relate to changes in other variables, particularly endurance (measured as the time-to-task failure at the same power output before and after training) and VO2max. To address these purposes, we examined the validity of CP as a threshold for steady-state and non-steady-state conditions and verified the matching of MICT and HIIT for total work, caloric expenditure, and average VO2 and HR. Finally, we observed the impact of MICT or HIIT training for 8 weeks on CP and endurance at the same power output.
Methods

Subjects

All recruiting of subjects was done in accordance with the approved methods of the Institutional Review Board at Brigham Young University. This study used a sample group of young adults, ages 18–35, who were untrained but otherwise healthy. All subjects also met the following exclusion criteria (24–27): (1) no history of cardiovascular disease or heart problems; (2) no history of smoking; (3) not currently taking any medications; (4) females were not pregnant (verified by a pregnancy test); (5) ages 18–35 years old; (6) untrained (i.e., those who do not run, bike, or row more than 1 mile more than once a week); (7) VO$_2$max values in men ($\leq$ 45 ml/kg/min) and women ($\leq$ 40 ml/kg/min) are below the 55th and 66th percentile, respectively, according to the American College of Sports Medicine (28).

After reviewing the requirements of the study, all subjects provided written informed consent and completed a health history questionnaire and a preexercise screening questionnaire (29) conducted by the researcher. Height, weight, and body composition were then measured and assessed in qualified subjects.

Procedures

A combination of three different protocols were used throughout this study. Protocol #1 (n = 5; 4 males, 1 female) demonstrated the proof of concept of CP as a threshold between steady-state and non-steady-state exercise. Protocol #2 (n = 6; 6 males) examined the acute metabolic demands of the MICT and HIIT endurance training programs used for the subsequent training study (i.e., Protocol #3). Protocol #3 (n = 22; 12 males, 10 females) examined how CP and other performance markers were influenced by 8 weeks of MICT or HIIT.
All tests and exercise training sessions were conducted in the Human Performance Research Center (HPRC) at Brigham Young University. Each visit to the lab for testing was separated by at least 24 hours. Prior to each test, subjects fasted for 2–4 hours (except for water), and were encouraged to refrain from alcohol, caffeine, and heavy or intense exercise for 12–24 hours prior to testing.

**Protocol #1: Proof of Concept of CP as a Steady-State and Sustainability Threshold**

Subjects completed 4 days of tests. On Day 1, subjects completed a DEXA scan, a maximal graded exercise test (GXT), and a verification test on a cycle ergometer to determine $\dot{V}O_2\text{max}$ and maximal work-rate max (GXTmax). On Day 2, subjects completed two cycling tests to task failure (i.e., CP tests) to determine CP. Day 3 consisted of the Wingate test and one additional CP test, and Day 4 consisted of a cycling test to task failure at 95% CP. Details of each test are described in the sections below: Assessment of Body Composition; Assessment of $\dot{V}O_2\text{max}$ and GXTmax; Verification of $\dot{V}O_2\text{max}$; Assessment of CP and $W'$; Assessment of Wingate Max and Average Power.

**Protocol #2: Comparison of the Acute Metabolic Demands of the MICT and HIIT Workouts**

Subjects completed 3 days of tests. On Day 1, subjects performed a GXT to determine $\dot{V}O_2\text{max}$ and GXTmax as well as a constant load verification test to confirm the $\dot{V}O_2\text{max}$ (see Assessment of $\dot{V}O_2\text{max}$ and GXTmax and Verification of $\dot{V}O_2\text{max}$). On Day 2, subjects performed a supervised MICT workout in which subjects maintained 44% GXTmax for the full 40-min duration. On Day 3, subjects performed a 40-min supervised HIIT workout, which began with a 6-min warm-up at 20% GXTmax. Subjects then performed four 4-min intervals at 80% GXTmax with 4-min active recovery intervals in between at 20% GXTmax. They then completed an active 6-min cooldown at 20% GXTmax. Oxygen consumption, caloric expenditure and HR heart rate
were measured during the HIIT and MICT workouts and for 30 min of seated rest after completing each workout. Note that the MICT and HIIT workouts studied in this protocol are the same as those used during the 8 weeks of training in Protocol #3.

**Protocol #3: Impact of 8 Weeks of MICT or HIIT on CP and Exercise Tolerance**

Subjects completed 4 days of baseline tests prior to beginning their training program. Days 1 through 4 followed a similar outline as Protocol #1 (Day 1: DEXA, GXT and verification test; Days 2–4: one to two CP tests per day). The fifth visit (i.e., the first training visit) included the Wingate test and the first training session (according to their assigned MICT or HIIT program). Following the pretraining testing, subjects were assigned to either the MICT (6, 7, 12, 30) or HIIT (6, 7, 12, 30, 31) group by matching the GXTmax in each group. The MICT and HIIT programs were identical to those outlined in Protocol #2. Heart rate was also measured on a subset of subjects during the second workout. All training sessions were supervised and took place on Life Fitness IC7 stationary bikes, with real-time feedback of power output (IC7 Indoor Cycle, Life Fitness, Rosemont, IL, USA).

After 4 weeks of training sessions, the subject’s body mass and GXTmax were remeasured to adjust the training intensity in accordance with any training adaptations that had occurred due to 4 weeks of training. If the subject’s GXTmax increased during the GXT at this point compared to the pretraining test, their respective training program was adjusted based on the new GXTmax for the last 4 weeks of the training program. After completing the 8 weeks of exercise training, subjects completed the same sequence of tests that were completed prior to training. Details of each test are described in the sections below: *Assessment of Body Composition; Assessment of $\dot{V}O_2$max and GXTmax; Verification of $\dot{V}O_2$max; Assessment of CP and $W'$; Assessment of Wingate Max and Average Power.*
Assessment of Body Composition with DEXA Scan

A DEXA scan was conducted on each subject according to the manufacturer’s suggestions to measure total body composition (specifically, total fat mass, total lean mass, leg fat mass, and leg lean mass) using the Lunar iDXA machine (Lunar iDXA, GE Healthcare, Chicago, IL, U.S.A) with the Lunar iDXA enCORE software (version 17) (25, 32).

Assessment of $\dot{V}O_2$max and GXTmax

$\dot{V}O_2$max of each subject was measured during a GXT on an electronically braked cycle ergometer (Corival cpet, Lode, Groningen, Netherlands). A metabolic measurement system and mouthpiece (True One, Parvo-Medics Inc., Sandy, UT, USA) were used to measure $\dot{V}O_2$ and other ventilatory parameters (33–35). Subjects wore a Polar heart rate monitor (Polar H9 Heart Rate Sensor, Polar, Bethpage, NY, USA) to measure heart rate. The exercise test began at 50–75 watts for 1 min and subsequently increased by 25 watts every min until task failure. Task failure was defined as the point when the subject could no longer maintain a self-selected pedaling frequency (between 70–90 RPM), despite strong verbal encouragement. The subject then performed a cooldown at approximately 50–75 watts for approximately 5 min. The highest 30-s average $\dot{V}O_2$ and HR measured during the test were considered the subject’s $\dot{V}O_2$max and HRmax. The last power output the subject was able to complete for a full min was considered their GXTmax. The criteria for a valid maximal GXT included achieving a respiratory exchange ratio (RER) greater than 1.1 and a maximal heart rate of $\pm$ 10 bpm of their age-predicted maximal heart rate (220 – age) (36). A verification test (see Verification of $\dot{V}O_2$max) was also conducted to confirm the $\dot{V}O_2$max and HRmax achieved (35, 37).
**Verification of \( \dot{V}O_2\text{max} \)**

A constant load verification test was conducted 30 min after completing the GXT and its accompanying cooldown. The purpose of this second test was to verify that the \( \dot{V}O_2\text{max} \) and HRmax reached during the GXT were the true \( \dot{V}O_2\text{max} \) and HRmax of the subject (35). The verification test was performed at a constant load representing 105% of the previously determined GXTmax. The verification test confirmed the \( \dot{V}O_2\text{max} \) achieved in the GXT if the \( \dot{V}O_2\text{max} \) during the verification test did not increase proportionally (i.e., \( \dot{V}O_2 \) reached during verification test was less than 5% greater than \( \dot{V}O_2 \) reached during GXT). The verification test utilized the same cycle ergometer, metabolic measurement system, and Polar heart rate monitor as were used during the GXT. The verification test began with a 5-min warm-up at 40% GXTmax, followed by a 5-min rest interval, and a 3-min warm-up at 40% GXTmax. The workload was then increased to 105% GXTmax. The subject was encouraged to maintain a pedaling frequency of 90 ± 5 RPM until task failure. Meanwhile, as soon as the workload increased to 105% GXTmax, a timer was started to determine exactly how long the subject was able to exercise at the given intensity prior to task failure. Once the subject could no longer consistently maintain 90 ± 5 RPM and task failure was achieved, the timer was stopped and the time to task failure was recorded. The workload on the bike was then reduced to approximately 40% GXTmax and the subject performed a 5-min cooldown. The \( \dot{V}O_2\text{max} \) reached during this test was also recorded. If the \( \dot{V}O_2\text{max} \) (or HRmax) obtained during this verification test was higher than what was recorded during the GXT, then the \( \dot{V}O_2\text{max} \) and/or HRmax obtained during the verification test was considered the true \( \dot{V}O_2\text{max} \) and/or HRmax of the subject.
Assessment of CP and W’

The assessment of CP and W’ was performed following the recommendations of Muniz-Pumares et al. (38). Specifically, 3–5 constant-load tests to task failure at different percentages of the subject’s GXTmax (16, 19, 38) were performed over the course of several days. The duration of each test was within approximately 2–15 min and allowed for at least 5 min between the shortest and the longest test (16, 19, 38). Only tests during which \( \dot{V}O_2 \) reached ± 5% of the previously determined \( \dot{V}O_2max \) were included in the final calculation of CP (16, 19, 38).

All tests were conducted using the same Lode cycle ergometer and Parvo-metabolic cart as used in the GXT and verification tests. Each assessment began with a 5-min warm-up at 40% GXTmax, a 5-min rest period, and a 3-min warm-up at 40% GXTmax. The power output was then increased to the preselected percentage of GXTmax (approximately 75%, 80%, 90%, or 100% GXTmax), and the subject was encouraged to maintain a pedaling frequency of 90 ± 5 RPM for as long as possible. As soon as the power output was raised, a timer was also started to measure time-to-task failure at this power output. Once the subject could no longer consistently maintain 90 ± 5 RPM, the timer was stopped and the time-to-task failure was recorded. The subject then performed a 5-min cooldown at approximately 40% GXTmax. The highest \( \dot{V}O_2 \) reached during each test was recorded to confirm that this assessment was an accurate assessment of CP.

Once all constant load tests were completed and met the above requirements, the total work performed during each test was graphed against the time-to-task failure for each test. Linear regression was subsequently performed to determine the slope (i.e., CP) and y-intercept (i.e., W’) of the line. If the standard error of the estimate for the slope was greater than 5% or the
standard error of the estimate for the y-intercept was greater than 10%, additional CP tests were performed to reduce the error (38).

Assessment of Wingate Max and Average Power

The 30-s Wingate test was conducted to measure anaerobic capacity, specifically, Wingate max power (WINmax) and average power (WINavg) (39–42). This test was performed with a Monark 894E cycle ergometer (Monark 894E, Monark Exercise AB, Vansbro, Sweden) with a weight basket and a computer with the Monark Anaerobic Test Software. Immediately prior to the test, the subject performed a 5-min warm-up at 44% GXTmax on a Life Fitness stationary bike. Then, the subject performed a 3–5 s sprint on the Monark cycle ergometer (unloaded) to familiarize themselves with the Monark cycle ergometer, followed by a 3-min rest period. During this 3-min rest, 7.5% of the subject’s body mass (kilograms) was added to the weight basket on the cycle ergometer as the brake weight. Following the 3-min rest period, the subject began pedaling. Over approximately 10 s, the subject increased their pedaling frequency to a sprint (≥ 100–110 RPM), at which time the basket containing the brake weight was dropped, adding resistance to the cycle ergometer. The 30-s timer on the computer automatically started once the brake weight was dropped, and the subject was encouraged to maintain the highest pedaling frequency possible throughout the 30-s test. The maximum power (WINmax) was defined as the highest power achieved over the course of 1 s while the average power (WINavg) was defined as the average power over the full 30 s of the Wingate test.

Statistical Analysis

All statistical analyses were performed using SPSS version 26 (SPSS Inc.). In Protocol #1, repeated measures ANOVA followed by Bonferroni-corrected t-tests were performed to determine differences in time and VO2 between CP tests. For Protocol #2, paired t-tests were
performed to determine differences between the MICT and HIIT workouts. For Protocol #3 independent sample t-tests were used to identify any significant differences in subject characteristics between the MICT and HIIT groups at baseline. Two-way repeated measures ANOVA were performed to compare pretraining values and posttraining values (e.g., CP, W’, endurance, absolute and mass-specific VO₂max, Wingate max and average power) between two independent groups (HIIT training vs. MICT training). In the event of a significant omnibus, post hoc analysis of planned comparisons with t-tests was performed. Independent sample t-tests were performed to compare the percent change in variables between each group while one-sample t-tests were performed to determine if there was a significant percent change in variables within each group. Pearson correlations were also performed to detect relationships between the training-induced changes in performance factors (e.g., change in VO₂max, change in CP and W’), and trend analysis was conducted to identify the relationship between training intensity and change in CP. A stepwise linear regression was performed to identify which independent variables best predicted the training-induced change in endurance. Data are expressed as the mean ± SE, and the alpha level was set to P ≤ 0.05 unless otherwise stated.

Results

Protocol #1: Proof of Concept of CP as a Steady-State and Sustainability Threshold

A set of five young adults (age 33.6 ± 4.3 years; 4 males, 1 female) completed a preliminary study to test the validity of our approach to measuring CP. As CP is said to separate steady state from non-steady-state exercise (9, 16, 20), time-to-task failure and VO₂ responses to exercise above and below CP were examined. VO₂ responses are presented as a percentage of VO₂max determined during a GXT. Figure 1A illustrates the relationship between exercise intensity (%CP) and time-to-task failure, revealing the typical (16, 43) hyperbolic power-
duration relationship. The time-to-task failure was significantly different (P < 0.01) between each intensity, with the greatest endurance being observed at 95% CP. Figure 1B further illustrates the different $\dot{V}O_2$ responses to the same exercise intensities as in Figure 1A. In agreement with previously reported observations (14), $\dot{V}O_2$ responses reached a submaximal steady state when exercising to failure below CP but not above CP (14). Specifically, when exercising 5% below CP, $\dot{V}O_2$ responses reached a very high steady state, maintaining 90.3 ± 2.1% $\dot{V}O_2$max and 96.8 ± 1.0% HRmax during the last 10 min of exercise. No subject reached $\dot{V}O_2$max during the 95% CP trial; $\dot{V}O_2$ was always submaximal (P = 0.01). When exercising at any intensity above CP (110%, 120%, 140% CP), steady-state conditions were never attained and $\dot{V}O_2$max was achieved in all cases. Specifically, the highest $\dot{V}O_2$ achieved in all trials above CP were not significantly different than the $\dot{V}O_2$max determined in a separate GXT (110% CP: 101.2 ± 2.6% $\dot{V}O_2$max, P = 0.67; 120% CP: 100.3 ± 3.9% $\dot{V}O_2$max, P = 0.94; 140% CP: 97.2 ± 3.0% $\dot{V}O_2$max, P = 0.40).

**Protocol #2: Comparison of the Acute Metabolic Demands of the MICT and HIIT Workouts**

A set of six young adult males (age 22.7 ± 0.4 years) completed a second preliminary study comparing the metabolic demands and caloric expenditure of a single session of the MICT and HIIT workouts used for training in Protocol #3. Subjects completed a single training session of the MICT protocol and a single session of the HIIT protocol on separate days. As depicted in Table 1, the two protocols were well-matched for total work and caloric expenditure (kCals). However, compared to the MICT training session, subjects reached a significantly higher percentage of their $\dot{V}O_2$max and HRmax (measured during the GXT) during the HIIT protocol, as shown in Figure 2A and 2B.
Protocol #3: Impact of 8 Weeks of MICT or HIIT on CP and Exercise Tolerance

**MICT and HIIT Group Comparisons—Retention and Total Work Completed**

Twenty-five subjects participated in this protocol. There were two dropouts from the MICT group (due to personal health circumstances unrelated to the training protocol) and one dropout from the HIIT group (due to COVID-19). Of the remaining 22 subjects, one subject missed one workout due to University-wide shutdowns associated with COVID-19 and one subject missed two workouts due to the same shutdowns. Otherwise, the MICT and HIIT groups completed 24 workouts at a rate of three workouts per week.

Ultimately, 22 young (age $26.4 \pm 0.9$ years) untrained but healthy individuals (12 males, 10 females) completed this protocol. As shown in Table 2, independent sample t-tests confirmed that the subjects in the MICT and HIIT groups did not significantly differ in terms of age, body composition, and performance prior to training. Importantly, CP did not differ between groups ($P = 0.97$).

The total work completed between the groups throughout the 8 weeks did not differ significantly (MICT: $5,622.5 \pm 453.3$ kJ vs. HIIT: $5,829.2 \pm 501.2$ kJ, $P = 0.76$). Heart rate as a percent of HRmax was measured on a subset of subjects (MICT: 8 subjects; HIIT: 9 subjects) during the second workout and on average the MICT group reached $79 \pm 2\%$ HRmax and the HIIT group reached $98.7 \pm 1.3\%$ HRmax ($P < 0.01$). The intensity of the MICT and HIIT exercise sessions, measured as a percent of CP, was $64.8 \pm 1.0\%$ CP in the MICT and $123.6 \pm 3.8\%$ CP in the HIIT ($P < 0.01$).

**Impact of MICT and HIIT on Body Composition**

Body mass was unaffected by training. Specifically, there was no significant interaction between training and group on body mass ($P = 0.35$), such that body mass did not significantly
change in the MICT group (70 ± 4.5 kg to 69.8 ± 4.4 kg) or HIIT group (85.9 ± 8.8 kg to 85 ± 8.5 kg). There was also no significant main effect of training detected (P = 0.15) and no significant main effect of group (P = 0.13). When body composition was narrowed to leg lean mass specifically, there remained no significant interaction between training and group (MICT: 16.0 ± 1.1 kg to 16.0 ± 1.1 kg; HIIT: 20.0 ± 2.0 kg to 20.0 ± 2.0 kg; P = 0.99). No significant main effect of training (P = 0.96) or main effect of group (P = 0.10) was detected for leg lean mass.

Impact of MICT and HIIT on CP

As shown in Figure 3A, there was a significant interaction between training and group, such that HIIT elicited a greater change in CP (140.3 ± 14.1 W to 176.1 ± 15.2 W) than MICT (139.7 ± 12.6 W to 160.8 ± 14.0 W; P = 0.03). There was also a significant main effect of training on CP (P < 0.01), such that CP increased, regardless of group. No significant main effect of group on CP was detected (P = 0.67).

As illustrated in Figure 3B, t-tests showed that when considered as a percent change CP significantly increased in both the MICT (15.7 ± 3.1%, P < 0.01) and HIIT (27.5 ± 4.3%, P < 0.01) groups, and the magnitude of the increase was significantly greater in the HIIT group than the MICT group (P = 0.04).

Impact of MICT and HIIT on W’

As shown in Figure 3C, W’ in the MICT group was 11.42 ± 1.3 kJ before and 12.0 ± 1.2 kJ after training. Work-prime in the HIIT group was 14.3 ± 1.9 kJ before and 15.2 ± 1.6 kJ after training. There was no significant interaction between training and group on W’ (P = 0.84), no significant main effect of training (P = 0.24) on W’ and no significant main effect of group on W’ (P = 0.16).
As illustrated in Figure 3D, t-tests showed that, when considered as a percent change, W’ did not significantly change in the MICT (9 ± 8.1%, P = 0.29) or the HIIT (12.9 ± 9.5%, P = 0.20) groups. Moreover, the magnitude of change in W’ was not significantly different between groups (P = 0.76).

**Impact of MICT and HIIT on Endurance (Time-to-Task Failure)**

The impact of MICT and HIIT training on endurance was measured by comparing the time-to-task failure when exercising at the same power output before and after training (95.6 ± 1.7% of the pretraining GXTmax; power output pre: 200.1 ± 12.6 W vs. power output post: 200.8 ± 12.4 W; P = 0.56). Overall, there was a significant interaction between training and group (P = 0.05; Figure 3E), such that MICT increased endurance at the same power output from 240.5 ± 32.7 s to 437.8 ± 53.3 s, and HIIT increased endurance at the same power output from 191.6 ± 10.5 s to 498.6 ± 47.3 s. There was also a significant main effect of training (P < 0.01) with endurance at the same power output increasing, regardless of group. No significant main effect of group on endurance at the same power output was detected (P = 0.90).

As illustrated in Figure 3F, t-tests showed that, when considered as a percent change, endurance at the same power output significantly increased in the MICT (88.6 ± 12.4%, P < 0.01) and HIIT (163.2 ± 24.2%, P < 0.01) groups. Moreover, the magnitude of change in endurance at the same power output was significantly greater in the HIIT group than the MICT group (P = 0.01).

**Impact of MICT and HIIT on V̇O₂max**

Although absolute V̇O₂max in the MICT group changed from 2.4 ± 0.2 L/min to 2.6 ± 0.2 L/min and HIIT changed from 2.6 ± 0.3 L/min to 2.9 ± 0.3 L/min, the interaction between training and group for absolute V̇O₂max did not reach significance (P = 0.15). However, a
significant main effect of training was detected for absolute \( \dot{VO}_2 \max \) (\( P < 0.01 \)), such that regardless of group, absolute \( \dot{VO}_2 \max \) increased from 2.5 ± 0.2 L/min to 2.8 ± 0.2 L/min. No significant main effect of group for absolute \( \dot{VO}_2 \max \) (L/min) was detected (\( P = 0.51 \)).

When considered as a percent change, t-tests showed that absolute \( \dot{VO}_2 \max \) (L/min) significantly increased in the MICT (8.3 ± 1.9%, \( P < 0.01 \)) and HIIT (13.2 ± 3.0%, \( P < 0.01 \)) groups. However, the magnitude of percent change in absolute \( \dot{VO}_2 \max \) (L/min) was not significantly different between the MICT and HIIT groups (\( P = 0.19 \)).

MICT changed mass-specific \( \dot{VO}_2 \max \) from 34.6 ± 2.0 ml/kg/min prior to training to 37.4 ± 2.1 ml/kg/min after training, and HIIT changed from 30.8 ± 1.7 ml/kg/min to 34.9 ± 1.9 ml/kg/min. While this interaction between training and group did not reach significance (\( P = 0.21 \)), the main effect of training on mass-specific \( \dot{VO}_2 \max \) did reach significance (\( P < 0.01 \)). No significant effect of group on mass-specific \( \dot{VO}_2 \max \) was detected (\( P = 0.25 \)).

When considered as a percent change, t-tests showed that mass-specific \( \dot{VO}_2 \max \) significantly increased in the MICT (8.3 ± 2.0%, \( P < 0.01 \)) and HIIT (14 ± 2.6%, \( P < 0.01 \)) groups. Though not reaching statistical significance, the magnitude of change in mass-specific \( \dot{VO}_2 \max \) tended to be greater in the HIIT group (\( P = 0.09 \)).

**Impact of MICT and HIIT on GXTmax**

Maximum power determined from the GXT (GXTmax) in the MICT group was 204.6 ± 17.8 W before training and 238.6 ± 18.6 W after training; GXTmax in the HIIT group was 213.6 ± 19.5 W before training and 268.2 ± 20.8 W after training. There was a significant interaction between training and group for GXTmax (\( P = 0.02 \)). There was also a significant main effect of training on GXTmax (\( P < 0.01 \)) but no significant main effect of group (\( P = 0.48 \)).
When considered as a percent change, t-tests revealed that GXTmax significantly increased in the MICT (17.6 ± 2.3%, P < 0.01) group and in the HIIT (27.3 ± 3.8%, P < 0.01) group. Moreover, the magnitude of change in GXTmax was significantly higher in the HIIT group (P = 0.04).

**Impact of MICT and HIIT on WINmax and WINavg**

Wingate max power (WINmax) in the MICT group was 681.3 ± 46.9 W before training and 716.3 ± 49.5 W after training; WINmax in the HIIT group was 773.9 ± 74.9 W before training and 820 ± 86.1 W after training. There was no significant interaction between training and group for WINmax (P = 0.73). There was a significant main effect of training on WINmax (P = 0.02) but no significant main effect of group (P = 0.30).

When considered as a percent change, t-tests revealed that WINmax significantly increased in the MICT (5.4 ± 2.3%, P = 0.04) group but not in the HIIT (6.2 ± 1.7%, P = 0.11) group. Moreover, the magnitude of change in WINmax was not significantly different between the MICT and HIIT groups (P = 0.82).

Wingate average power (WINavg) for the full 30 s of the Wingate test changed in the MICT group from 483 ± 46.3 W to 489.9 ± 42.8 W, and the HIIT group changed from 580.4 ± 68.7 W to 610.6 ± 68.4 W, but the interaction between training and group did not reach significance for WINavg (P = 0.06). However, a significant main effect of training was detected for WINavg (P < 0.01). No significant main effect of group was detected (P = 0.20).

When considered as a percent change, t-tests revealed that WINavg did not significantly change in the MICT group (2.5 ± 1.6%, P = 0.16) but significantly increased in the HIIT group (6.3 ± 1.7%, P < 0.01). Moreover, the magnitude of change in WINavg was not significantly different between the MICT and HIIT groups (P = 0.13).
**Relationship Between Training-Induced Improvements in Endurance and Physiological Variables**

Several Pearson correlations were also performed to determine any significant correlations between the main variables—percent change in CP, W’, and \( \dot{V}O_2 \)max—and the improvement in endurance (i.e., change in time-to-task failure at the same power output). The percent change in mass-specific \( \dot{V}O_2 \)max was significantly correlated with the percent change in endurance (\( r = 0.49; P = 0.02 \); Figure 4A). The percent change in CP and in W’ were also significantly related to the percent change in endurance (\( r = 0.60; P < 0.01 \); \( r = 0.47; P = 0.03 \), respectively; Figure 4B and 4C). Subsequently, a stepwise linear regression was performed to determine which of the following changes associated with training (percent change in CP, W’, mass-specific \( \dot{V}O_2 \)max, \( W_{INmax} \), \( W_{INavg} \), lean leg mass) were meaningfully and independently related to the training-induced increase in endurance. Ultimately, stepwise linear regression yielded two significant, independent predictors: (1) percent change in CP and (2) percent change in W’) accounting for 77% of the variance (\( R^2 = 0.77; P < 0.01 \)) in the training-induced increase in endurance at the same power output. Notably, stepwise linear regression indicated that factors like the training-induced change in mass-specific \( \dot{V}O_2 \)max and leg lean mass did not significantly account for any variance that was not already accounted for by CP and W’.

**Relationships Between CP and Other Physiological Variables**

To further understand why CP improved, or what influenced the improvements, a Pearson correlation was performed to identify if the percent change in mass-specific \( \dot{V}O_2 \)max was correlated to the percent change in CP or the percent change in W’. As shown in Figure 5A, there was no significant correlation between the change in mass-specific \( \dot{V}O_2 \)max and the change in CP (\( r = 0.29; P = 0.18 \)). There was, however, a significant correlation between the change in
mass-specific $\dot{V}O_2\text{max}$ and the change in W' ($r = 0.56; P < 0.01$; Figure 5B), such that subjects who had greater increases in W’ also had greater increases in mass-specific $\dot{V}O_2\text{max}$. A trend analysis was also performed on the training intensity (as a percent of baseline CP) and the percent change in CP, which indicated a significant positive curvilinear relationship ($r = 0.70; P < 0.01$; Figure 6). When isolating this relationship by group, the percent change in CP in the MICT group was not significantly related to the training intensity ($r = 0.52; p = 0.09$), whereas the change in CP in the HIIT group was significantly related to the training intensity ($r = 0.76; p < 0.01$).

To more fully understand the impact of CP changes as part of the power-duration relationship, CP was also considered as a percent of GXTmax and as a percent of WINmax. When CP was measured as a percent of GXTmax, no significant interaction was detected between training and group (MICT: 68.1 ± 1.1% to 67 ± 1.5%; HIIT: 65.3 ± 1.9% to 65.3 ± 1.6%; $P = 0.69$) nor a main effect of training ($P = 0.66$). No significant main effect of group was detected for CP as a percent of GXTmax either ($P = 0.22$).

T-tests revealed that, when considered as a percent change, CP as a percent of GXTmax did not significantly change in the MICT ($-1.4 \pm 2.6\%, P = 0.23$) group but did significantly increase in the HIIT ($0.5 \pm 2.9\%, P < 0.01$) group. Moreover, the magnitude of change in CP as a percent of GXTmax was not significantly different between the MICT and HIIT groups ($P = 0.64$).

When CP was measured as a percent of WINmax, no significant interaction was detected between training and group (MICT: 20.4 ± 0.9% to 22.5 ± 1.2%; HIIT: 18.3 ± 0.7% to 21.9 ± 0.7%; $P = 0.22$), however there was a significant main effect of training ($P < 0.01$), such that
both groups increased the percentage of WINmax at which CP occurred. No significant main
effect of group was detected for CP as a percent of WINmax (P = 0.27).

T-tests revealed that, when considered as a percent change, CP as a percent of WINmax
significantly increased in the MICT (10.3 ± 3.7%, P = 0.02) and HIIT (21.4 ± 6.3%, P < 0.01)
groups. However, the magnitude of change in CP as a percent of WINmax was not significantly
different between the MICT and HIIT groups (P = 0.14).

Discussion

The purpose of this study was to investigate how HIIT and MICT endurance training
influence CP and W’ and other performance variables. We also sought to understand how any
changes in CP and W’ relate to the other performance variables and their respective changes,
especially endurance and VO₂max. The data indicate that even when MICT and HIIT were well-
matched for total work, time, caloric expenditure and average HR and VO₂ achieved, the
adaptations after 8 weeks of training still differ significantly, such that HIIT increased CP to a
greater degree than MICT. Moreover, the changes in endurance were better captured by changes
in CP and W’ than traditional measures, like VO₂max. These findings and their implications will
be further examined in the following sections.

Critical Power as a Maximal Metabolic Steady State: Proof of Concept

Critical Power is often described as the highest power output that can be sustained during
steady-state exercise conditions (i.e., maximum metabolic steady state), but multiple approaches
exist to determine CP. In Protocol #1, we sought to determine the construct validity of our
approach to determining CP. As illustrated in Figure 1, CP was determined by having subjects
perform multiple tests to task failure at various percentages of GXTmax. Only tests that elicited
task failure and reached VO₂max (± 5%) within 2–15 min were included in the calculation of
CP. Following the calculation of CP, a group of five subjects exercised at 95% CP until task failure to determine if our approach to measuring CP was reflective of the transition between compensable, steady-state exercise and noncompensable, non-steady-state exercise. In agreement with previously reported data (14, 16), time-to-task failure was exponentially greater below CP than above CP (Figure 1A). As illustrated in Figure 1B, exercise at 95% CP (73.4 ± 0.7% GXTmax) yielded a very high metabolic steady state (average of 90.3 ± 2.1% \( \dot{V}O_2 \text{max} \) and 96.8 ± 1.0% HRmax during the last 10 min of exercise) that never reached \( \dot{V}O_2 \text{max} \) (\( P = 0.01 \)), while all intensities above CP ultimately led to \( \dot{V}O_2 \text{max} \). These findings are consistent with the explanation by Jones et al. (9) that CP represents a separation between “[powers at which] distinct physiological response behaviors” occur. These findings are also in agreement with those of Burnley et al. (18) and Poole et al. (16). Together, these data support the validity of our approach to assessing CP and the notion that CP separates compensable, steady-state exercise from noncompensable, non-steady-state exercise.

**Do HIIT and MICT Training Impact CP, W’ and Endurance?**

In Protocol #2, subjects performed a single session of the MICT and HIIT protocols while metabolic rate and heart rate were measured. As illustrated in Table 1 and Figure 2, the total work, total oxygen consumption and caloric expenditure during and after exercise did not differ between the MICT and HIIT workouts. Nevertheless, subjects reached a higher percentage of \( \dot{V}O_2 \text{max} \) and HRmax during the HIIT (\( \dot{V}O_2: 94.8 \pm 2.5\% \dot{V}O_2 \text{max} \), HR: 97.5 ± 1.9% HRmax) protocol than the MICT protocol (\( \dot{V}O_2: 66.6 \pm 0.9\% \dot{V}O_2 \text{max} \), HR: 83.5 ± 7.7% HRmax).

In Protocol #3, 22 subjects completed 8 weeks of MICT training (\( n = 11 \)) or HIIT training (\( n = 11 \)). As described in Table 2, the two groups were well-matched at baseline. Despite reaching very different levels of HRmax during the training protocols (MICT: 79 ± 2% HRmax;
HIIT: 98.7 ± 1.3% HRmax; P < 0.01), the two groups performed a nearly identical amount of work over the 8 weeks of training (MICT: 5,622.5 ± 453.3 kJ vs. HIIT: 5,829.2 ± 501.2 kJ, P = 0.76). Overall, these data indicate that the two protocols were well-matched in terms of total work.

As illustrated in Figures 3A and 3B, and in agreement with Gaesser et al. (23), both MICT and HIIT significantly increased CP. However, our most novel finding was that, despite performing a similar amount of work over the course of 8 weeks, the HIIT group (27.5 ± 4.3%) experienced an increase in CP that was nearly twice that of the MICT group (15.7 ± 3.1%) (Figure 3B). The greater increase in CP among the HIIT group is in contrast to the findings of Gaesser et al. (23), who reported that MICT and HIIT increased CP to the same extent in relatively fit males. Differences in the sample population and size as well as the lack of matching for work completed by each group may account for these differences. In contrast to Gaesser et al. (23), we used a larger sample (22 vs. 11) of previously untrained females and males in our study, and our MICT and HIIT workouts were matched for work completed.

Several other studies have reported that CP is sensitive to endurance training. For example, Vanhatalo et al. (44) found significant increases in CP after 4 weeks of HIIT. However, the study by Vanhatalo et al. did not compare the effects of HIIT to MICT due to other primary purposes (44). In 1992, Jenkins et al. found that 8 weeks of endurance training increased CP by 30% (45). Nevertheless, any increase in CP suggests that the individual can exercise at a higher intensity before accumulating a noncompensable amount of metabolic disturbance, but a larger increase in CP suggests even greater performance related improvements.

As illustrated in Figure 3C and 3D, W’ was not significantly, or consistently, impacted by MICT or HIIT training. Our findings that W’ did not significantly change in either group or
between groups are consistent with Gaesser et al. (23) and Vanhatalo et al. (44), who also found no significant changes in W’ after endurance training. Thus, the work able to be performed above CP before task failure does not appear to be as influenced by MICT or HIIT endurance training. However, the high intensity exercise in the form of sprint training (also referred to as supramaximal interval training) conducted by Jenkins et al. (5 bouts of 60-s Wingate sprints) significantly increased W’ (but did not change CP) after 8 weeks of sprint training (46). This suggests that adjusting the training stimulus to be much shorter (60 s) and supramaximal (consequently well above the CP threshold) may be more impactful on W’ than the more common endurance training programs MICT or HIIT.

As illustrated in Figure 3E and 3F, endurance at the same power output (~95% pretraining GXTmax) increased in both groups, but to a greater extent in the HIIT group than the MICT group. Since CP has been considered highly correlated with endurance (9), this indicates that an increase in CP, in the absence of a change in W’, is sufficient to improve endurance.

Why Did Endurance Increase?

As mentioned previously, MICT and HIIT induced changes to multiple performance variables, including CP, W’, VO₂max, GXTmax, WINmax, and WINavg. Changes in VO₂max are often used to assess the efficacy of a training program (6, 12), but have often been reported to not effectively predict changes in endurance (47, 48). Indeed, Vollaard et al. reported that the training-induced change in time-to-task failure was completely unrelated to training-induced changes in VO₂max (48). With this in mind, we sought to determine if changes in endurance are more related to CP and W’ than to VO₂max (9). Figure 4 illustrates that the change in VO₂max, CP and W’ were all significantly correlated with the change in endurance, with changes in CP being the most strongly related. Subsequently, training-induced changes in CP, W’, VO₂max, leg
mean mass and WINmax were entered into a stepwise linear regression to determine which
training-related changes were most independently predictive of the training-induced increase in
endurance at the same power output. Ultimately, the stepwise linear regression only included two
variables (CP and W’), which accounted for a majority (~77%) of the change in endurance.
Notably, changes in VO2max and lean mass did not provide any additional predictive value.
Consequently, changes in CP and W’ appear to better capture training-induced increases in
endurance performance than changes in VO2max (9, 16, 45).

**How and Why Did CP and W’ Increase?**

Since CP increased independently of W’, and, again, VO2max is often referred to as the
most important endurance performance factor (49), we wanted to know if the changes in CP and
W’ were correlated with changes in VO2max. Both MICT and HIIT training elicited significant
increases in VO2max (although not significantly between groups). Consistent with previous
observations (6–8), the training-induced increase in mass-specific VO2max tended (P = 0.09) to
be greater among the HIIT group than the MICT group. Notably, the training-induced increase in
VO2max in both groups (~2.9–25.1%) was substantially less than the training-induced increase
in CP (4.3–60.9%). As illustrated in Figure 5A, the training-induced increase in CP was not
significantly related to the training-induced increase in VO2max. Similar to our findings, Jenkins
et al. reported that the training-induced increase in CP (~30%) was not significantly correlated
(r = 0.32; P > 0.05) to the training-induced increase in VO2max (45). Gaesser et al. also reported
that the training-induced increases in CP were not related to or dependent upon changes in
VO2max (23). Together, these findings indicate that CP and VO2max are distinct physiological
variables, and consequently one cannot expect changes in one to be reflective of changes in the
other (Figure 5A). Although not the focus of this study, it seems likely that adaptations within
the muscle (e.g., enhanced skeletal muscle oxygen delivery and diffusion, or mitochondrial function) are involved in the improvements in CP that are not captured by \( \dot{V}O_2 \text{max} \) (16).

While the training-induced increase in \( \dot{V}O_2 \text{max} \) was not related to changes in CP, it was found to relate to changes in W’ (Figure 5B). We suggest this could be in part due to CP relying on steady-state conditions not reaching \( \dot{V}O_2 \text{max} \) (9, 16, 50) while working above CP (i.e., utilizing W’) indicates that reaching \( \dot{V}O_2 \text{max} \) and task failure is imminent (9, 16, 50). Thus, W’ and \( \dot{V}O_2 \text{max} \) appear to be more related than CP and \( \dot{V}O_2 \text{max} \).

Furthermore, the changes in CP were also correlated with the training intensity (as a percent of CP), such that the greater the intensity of training (expressed as a percentage above CP), the greater the increase in CP after 8 weeks of training. Specifically, a trend analysis illustrated a significant positive curvilinear relationship (Figure 6).

**How Do CP and W’ Relate to Endurance?**

Along the power-duration curve, it is clear that higher powers (or intensities of exercise) are less maintainable (16, 18, 51), with an individual’s max power (commonly indicated by the GXTmax) as the typical furthest right point along the curve. When comparing an individual’s CP as a percentage of this GXTmax, we expected to see this percentage increase with endurance training, thus illustrating a greater percentage of the GXTmax was sustainable before accumulating a noncompensable amount of metabolic disturbance. However, we saw no significant changes in CP as a percent of GXTmax. We believe part of this could be accounted for by changes in GXTmax itself (which increased significantly in both groups and between groups).

However, when performing a Wingate test, individuals reach much higher power outputs than during a GXT. Thus, the maximum power achieved during the Wingate test (WINmax)
potentially could be a better reference for the true max power achievable by an individual. With this in mind, when examining CP as a percentage of WINmax, we found that this percentage did significantly increase in both groups after training. Although we expected to see significant differences between groups as well, this finding does suggest that endurance training (whether MICT or HIIT) will increase the portion of maximal power that is metabolically compensable. This is similar to the ideas of Joyner et al. (49) and Dekerle et al. (51), who explained that elite athletes must be able to operate at a higher percentage of their \( \dot{V}O_2 \text{max} \) for a prolonged duration in order to remain competitive in races. Although \( \dot{V}O_2 \text{max} \) is a distinctly different metric than max power (GXTmax or WINmax), the theory remains plausible that CP represents a portion of one’s maximum capacity that is sustainable or compensable.

**Practical Application: Training Prescribed by CP**

As is common, exercise training for the present study was prescribed and personalized according to the results of a GXT. Despite performing exercise at the same percentage of GXTmax (often erroneously referred to as a percent of \( \dot{V}O_2 \text{max} \)), there was substantial variability in the training-induced changes in CP within each group. On average, the HIIT groups experienced a much larger change in CP, but even among the subjects of the HIIT group, there was substantial variability in the training-induced changes in CP, despite exercising at the same percentage of GXTmax.

Critical power is known to separate exercise domains of very distinct physiology. Exercise below CP results in little metabolite accumulation (14, 52), while exercise above CP results in progressively more metabolite accumulation (14, 52). Importantly, CP does not occur at a fixed percentage of GXTmax (e.g., subjects in our study ranged from 54.2% to 73.6% GXTmax). From the prescription of the training programs for the present study (MICT: 44%
GXTmax; HIIT: 20% and 80% GXTmax), we found that even within groups, subjects were exercising at very different percentages of their CP (MICT: 63% to 83% CP; HIIT: 117.1% to 162.2% CP). We believe these differences in training intensity influenced the magnitude of improvement in CP and endurance.

As Egan et al. demonstrated, to specifically receive the modulation of skeletal muscle gene expression (i.e., endurance exercise-induced muscle adaptations), one must elicit the proper stimulus to then elicit the homeostatic perturbation (e.g., decreased oxygen diffusion to the muscle; increased acidity from larger ratios of NAD+:NADH; or increased Pi accumulation from larger ratios of AMP:ATP) (15) which will signal for adaptations within the body to meet the new demand (15). Although, both MICT and HIIT endurance programs stimulate these pathways, since HIIT occurs in higher exercise intensity domains it stimulates these pathways to a greater extent, thereby potentially eliciting greater adaptations (13, 15, 52). Also, HIIT that specifically occurs in the severe exercise domain (above CP) would stimulate these pathways to an even greater extent than HIIT occurring in the heavy exercise domain (below CP).

As illustrated in Figure 6, the intensity of exercise, relative to CP, accounted for a significant amount of the variability in training-induced changes in CP. Across all groups, training-induced changes in CP appeared to increase exponentially when exercise reached an intensity of CP. Specifically, among the HIIT group, there was a strong linear relationship \(r = 0.76, P < 0.01\) between how far above CP the high intensity intervals were and how much CP increased with training, meaning that the intensity of exercise, in relation to CP, accounted for approximately 60% of the variability in training-induced changes in CP among the HIIT group. These data, in conjunction with the findings of Iannetta et al. (13) and many others, raise
the possibility that exercise prescription may be more personalized and more effective if prescribed relative to CP rather than GXT\text{max}, \bar{\text{VO}}_2\text{max}, or HR\text{max}.

Therefore, we suggest future studies to examine the effects of HIIT training at different percentages above CP. Recent studies by Berge et al. in 2021 (11) and Casado et al. in 2020 (53) also suggest that combining various types of exercise sessions in one program can also be very beneficial to endurance performance. Therefore, we also suggest future studies to examine the effects of mixed programs—alternating sessions of HIIT above CP, exercises at CP (i.e., tempo ride or run), and MICT—on endurance performance and CP. Other further areas of research should also include the effects of training in other populations, such as older age groups and already-trained individuals, on improving their CP (20). Such studies could identify more effective exercise training programs to improve function and quality of life in other populations.

Conclusions

Critical power distinguishes between compensable steady-state exercise and noncompensable, non-steady-state exercise (9, 14, 16, 52). This threshold also distinguishes between the heavy and severe exercise domains, which determine the physiological response of the muscle (13, 15, 16). HIIT, especially when performed above the CP threshold, increases CP and endurance (i.e., time-to-task failure at the same power output) to a greater extent than MICT. Importantly, how far above the CP threshold an exercise is appears to influence the training-induced adaptations in CP. Moreover, training-induced changes in CP and W’ are more strongly correlated with improvements in endurance than changes in \bar{\text{VO}}_2\text{max}, suggesting that important functional adaptations could be overlooked if \bar{\text{VO}}_2\text{max} is the only outcome monitored. With this in mind, future studies should examine the effect of prescribing exercise and examining function
changes with respect to CP rather than the variable $\dot{V}O_{2}\text{max}$, GXTmax, or HRmax parameters (13).


47. Davies KJA, Packer L, Brooks GA. Biochemical adaptation of mitochondria, respiration to endurance muscle, and whole-animal training logical condition of chronic ethanol consumption, liver concentrations of certain clusters (N-2, N-3, N-4) are not constant but may decrease 20-30. Arch Biochem Biophys. 1981;299(2):539–54.


Figure 1: Proof of Concept of CP as a Threshold for Steady-State Conditions
(A) Time-to-task failure and (B) $\dot{V}O_2$ when performing cycling exercise above or below CP. a: significantly different end time or end $\dot{V}O_2$ than test at 95% CP. b: significantly different end time or end $\dot{V}O_2$ than test at 110% CP. c: significantly different end time or end $\dot{V}O_2$ than test at 120% CP. d: significantly different end time or end $\dot{V}O_2$ than test at 140% CP. v: significantly different $\dot{V}O_2$ than $\dot{V}O_2_{\text{max}}$. (P < 0.05). CP = critical power.
Figure 2: Comparison of the Acute Metabolic Demands of MICT and HIIT Workouts

(A) MICT workout. (B) HIIT workout. Note that VO₂ max and work-rate max (GXT max) were determined by a graded exercise test (GXT) on a separate day. MICT = moderate intensity continuous training; HIIT = high intensity interval training.
Figure 3: Impact of 8 Weeks of MICT or 8 Weeks of HIIT on CP, W’, and Endurance
(A) Pre to post change in CP between MICT and HIIT; (B) Percent change in CP between MICT and HIIT; (C) Pre to post change in W’ between MICT and HIIT; (D) Percent change in W’ between MICT and HIIT; (E) Pre to post change in endurance (time-to-task failure at 200 ± 12 watts) between MICT and HIIT; (F) Percent change in endurance (time-to-task failure at 200 ± 12 watts) between MICT and HIIT. #significantly different from baseline (P < 0.05). *significantly different between groups (P < 0.05).
MICT = moderate intensity continuous training; HIIT = high intensity interval training; CP = critical power; W’ = work-prime; Endurance = time-to-task failure at a given power output.
Figure 4: Relationship Between Training-Induced Changes in Physiological Variables and Endurance

(A) Percent change in mass-specific VO₂max versus percent change in endurance (time-to-task failure at 200 ± 12 watts); (B) Percent change in CP versus percent change in endurance (time-to-task failure at 200 ± 12 watts) (C) Percent change in W' versus percent change in endurance (time-to-task failure at 200 ± 12 watts). MICT = moderate intensity continuous training; HIIT = high intensity interval training.
Figure 5: Relationship Between Training-Induced Changes in $\dot{V}O_{2}\text{max}$ and CP and W’
(A) Percent change in mass-specific $\dot{V}O_{2}\text{max}$ versus percent change in CP; (B) Percent change in mass-specific $\dot{V}O_{2}\text{max}$ versus percent change in W’. CP = critical power; W’ = work-prime; MICT = moderate intensity continuous training; HIIT = high intensity interval training.
Figure 6: Relationship Between Training Intensity and the Training-Induced Increase in CP. Note that training intensity is expressed as a percent of CP. CP = critical power; MICT = moderate intensity continuous training; HIIT = high intensity interval training.

\[ y = 23.2 - 0.004x^2 + 0.00003x^3 \]

\[ r = 0.70, P < 0.01 \]
Table 1: Metabolic and Caloric Differences Between MICT and HIIT Workouts

<table>
<thead>
<tr>
<th></th>
<th>MICT</th>
<th>HIIT</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total work (joules)</td>
<td>5133.3 ± 185.5</td>
<td>5133.3 ± 185.5</td>
<td>0.35</td>
</tr>
<tr>
<td>Total oxygen consumed during exercise (L/min)</td>
<td>85.7 ± 2.6</td>
<td>87.4 ± 5.6</td>
<td>0.32</td>
</tr>
<tr>
<td>Total oxygen consumed 30 min postexercise (L/min)</td>
<td>13.8 ± 0.92</td>
<td>14.1 ± 0.64</td>
<td>0.58</td>
</tr>
<tr>
<td>Total caloric expenditure during exercise (kCals)</td>
<td>419.7 ± 12.5</td>
<td>434.9 ± 11.7</td>
<td>0.11</td>
</tr>
<tr>
<td>Total caloric expenditure 30 min postexercise (kCals)</td>
<td>66.5 ± 4.2</td>
<td>67 ± 2.7</td>
<td>0.85</td>
</tr>
<tr>
<td>Highest ( \dot{V}O_2 ) reached (% ( \dot{V}O_2)max)</td>
<td>66.6 ± 0.9</td>
<td>94.8 ± 2.5</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Average ( \dot{V}O_2 ) reached (% ( \dot{V}O_2)max)</td>
<td>58.5 ± 1.0</td>
<td>59.7 ± 2.7</td>
<td>0.31</td>
</tr>
<tr>
<td>Highest HR reached (% HRmax)</td>
<td>83.5 ± 7.7</td>
<td>97.5 ± 1.9</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Average HR reached (% HRmax)</td>
<td>77.1 ± 2.6</td>
<td>77.3 ± 2.0</td>
<td>0.89</td>
</tr>
</tbody>
</table>

MICT = moderate intensity continuous training; HIIT = high intensity interval training
| Table 2: Subject Characteristics Within MICT and HIIT Groups at Baseline |
|---------------------------------|--------|--------|--------|
|                                 | MICT   | HIIT   | P-value|
| Age (years)                     | 26 ± 1.5 | 26.8 ± 1.1 | 0.66   |
| Height (cm)                     | 171.4 ± 4.3 | 172.4 ± 3.0 | 0.84   |
| Body Mass (kg)                  | 70.0 ± 4.5 | 85.9 ± 8.8 | 0.12   |
| Leg Lean Mass (kg)              | 15.9 ± 1.1 | 20.0 ± 1.9 | 0.10   |
| Total Lean Mass (kg)            | 46.1 ± 3.1 | 55.1 ± 4.9 | 0.15   |
| Critical Power (W)              | 139.7 ± 12.6 | 140.3 ± 14.1 | 0.97   |
| Work-Prime (kJ)                 | 11.4 ± 1.3 | 14.3 ± 1.9 | 0.23   |
| ñVO₂max (ml/kg/min)             | 34.6 ± 2.0 | 30.8 ± 1.7 | 0.15   |
| ñVO₂max (L/min)                | 2.4 ± 0.2 | 2.6 ± 0.3 | 0.66   |
| GXTmax (W)                      | 204.6 ± 17.8 | 213.6 ± 19.5 | 0.73   |
| Wingate Max Power (W)           | 681.3 ± 46.9 | 773.9 ± 74.9 | 0.31   |
| Wingate Average Power (W)       | 482 ± 46.3 | 580.4 ± 68.7 | 0.25   |

MICT = moderate intensity continuous training; HIIT = high intensity interval training; W = Watt. Note that work-rate max (GXTmax) was determined by a graded exercise test (GXT).