AN ABSTRACT OF THE THESIS OF

Aaron J. Seipel for the degree of Master of Science in Kinesiology presented on December 4th, 2018.

Title: The Influence of the Speed-Time Relationship on Testing for Aerobic Fitness.

Abstract approved: ____

Jason T. Penry

Maximal aerobic capacity ($\dot{V}O_{2max}$) is the most widely used measure for assessing cardiorespiratory fitness. It is a strong contributor to performance in endurance sports, predicts functional capacity in older adults, and is related to overall disease risk. As such, it is important that testing methodologies for determining $\dot{V}O_{2max}$ provide valid and reliable measurements. Despite the widespread use of $\dot{V}O_{2max}$, challenges exist whether using field or laboratory tests. With field testing, other physiologic variables have the potential to influence performance independent of $\dot{V}O_{2max}$. During lab testing, despite direct gas exchange measurement, many individuals fail to achieve a plateau in ventilatory oxygen consumption. The intensity-time relationship [critical speed (CS), and the curvature constant (W')] has the potential to influence performance in both of these testing environments, as its components effectively predict exercise tolerance in the severe intensity domain. To this end, this study examined the influence of the CS-W' relationship on performance during a commonly used field test, the Cooper 12-Minute Run (12MR), and on the measurement of $\dot{V}O_{2max}$ during a traditional graded exercise test. Thirty individuals (15 male, 15 female) with varied levels of running experience volunteered for and completed this study. Each subject performed the following tests over four visits in a randomized order: one maximal graded treadmill exercise test, six runs to volitional exhaustion (90 seconds – 12 minutes duration, split over two lab visits), and a maximal 12-minute run. For the 12MR, multiple regression analyses showed a significant positive correlation between 12MR distance and $\dot{V}O_{2max}$ ($r = 0.888$; $p < 0.05$), but was not statistically significant for W' ($r = 0.160$; $p = 0.845$). Bland-Altman plots showed no apparent bias for either prediction method by distance, but was different from zero ($p < 0.05$) for both $\dot{V}O_{2max}$ (mean difference = -163.52 m) and CS-

W' (mean difference = -143.53 m), with wider limits of agreement for $\dot{V}O_{2max}$ than CS-W' (LoA: -819.42 to +492.38 m vs -403.86 to +116.80 m). For $\dot{V}O_{2max}$, both CS and W' were found to contribute significantly to variance observed in $\dot{V}O_{2max}$ ($sp^2 = 0.803$ and 0.095, respectively; $p < 0.01$), with overall $R^2 = 0.828$. These data provide additional evidence of the link between 12MR performance and aerobic capacity, while supporting its use to track $\dot{V}O_{2max}$ over time without concern for changes in W' influencing results. They do, however, suggest that W' may influence the measurement of $\dot{V}O_{2max}$ during lab testing, although it is unclear whether this is due to the $\dot{V}O_2$ slow component or differences in anaerobic capacity. Nonetheless, when testing individuals who test administrators anticipate to have a low anaerobic capacity, adjusting test protocols to minimize time in the severe intensity domain may be warranted. Given the large proportion of $\dot{V}O_{2max}$ variation that the CS-W' model accounted for though, using these variables as a proxy for $\dot{V}O_{2max}$ may be another alternative for assessing aerobic fitness.

The Influence of the Speed-Time Relationship on Testing for Aerobic Fitness

by
Aaron J. Seipel

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented December 4, 2018
Commencement June 2019

Master of Science thesis of Aaron J. Seipel presented on December 4th, 2018

APPROVED:

Major Professor, representing Kinesiology

Head of the School of Biological and Population Health Sciences

---

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Aaron J. Seipel, Author

ACKNOWLEDGEMENTS

Thank you Jay Penry for your guidance and friendship over the past several years. Your care for balancing your students' overall wellbeing with their academic success is unparalleled.

Thank you to my graduate committee, Tony Wilcox, Sean Newsom, and Erica McKenzie for your support and input throughout the thesis process.

Thank you Staci Bronson for introducing me to the research process and for marking a clear course for my graduate school experience.

Thank you Morgan Anderson for sharing in the highs and lows of graduate school, both academically and athletically. Your friendship is a bright light that has been invaluable over the last couple years.

Thank you Micah White, Arthur Chan, and Stephanie Burleson for your help with the data collection process. This would have been a lot of tests to run all on my own.

Thank you to my participants for your time, your effort, and your willingness to show up a whole three more times after your first visit!

Thank you Emile Chol, Kevin Le, and many others from the OSU Triathlon Club for being good training partners and good friends. Balancing the stresses of academics with triathlon has been essential for my mental health throughout graduate school.

Thank you coach Kirsten Sweetland for your patience and flexibility over the past year. Sharing your experience has been invaluable, and your support has been essential in finding this balance between academics and athletics.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICIES

LIST OF ABBREVIATIONS

12-minute run test – 12MR

American College of Sports Medicine – ACSM

Critical intensity – CI

Critical power – CP

Critical speed – CS

Curvature constant of the intensity-time relationship – W’

Deoxyhemoglobin breakpoint

Distance predicted for the 12-minute run by the CS-W’ model – $D_{CSW'}$

Distance predicted for the 12-minute run by $\dot{V}O_{2max}$ – D_{VO2}

Distance ran during 12-minute run test – D_{12MR}

Heart rate – HR

Institutional review board – IRB

Intensity – I

Limits of agreement – LoA

Maximal accumulated oxygen deficit – MAOD

Maximal graded exercise test – GXT_{max}

Maximal lactate steady state – MLSS

Maximal oxygen consumption – $\dot{V}O_{2max}$

Power output – P

Rating of perceived exertion – RPE

Respiratory compensation point – RCP

Respiratory exchange ratio – RER

Time to exhaustion – TE

Volume of carbon dioxide expiration – $\dot{V}CO_2$

Volume of oxygen consumption – $\dot{V}O_2$

CHAPTER 1: LITERATURE REVIEW

Maximal Aerobic Capacity

Background

In assessing an individual's cardiorespiratory fitness, an individual's maximal rate of oxygen consumption ($\dot{V}O_{2max}$) is arguably the most common measure. $\dot{V}O_{2max}$ is a strong predictor of endurance performance and functional capacity[1,2], and thus can be used to track changes over time[3] or describe training intensity.

Increasing endurance exercise intensity is largely reliant on increases in aerobic metabolic activity, as reflected by increasing oxygen consumption ($\dot{V}O_2$). As muscular contraction relies on ATP hydrolysis, increasing mitochondrial ADP concentrations stimulate oxidative phosphorylation in the electron transport system, thus increasing the demand for oxygen as the ultimate electron acceptor[4]. As such, factors limiting the transport of environmental oxygen to the mitochondrial level, are also expected to limit an individual's $\dot{V}O_{2max}$[5,6].

Applications in Health and Fitness

Current guidelines from the American College of Sports Medicine (ACSM) base training recommendations for aerobic activities on percentages of $\dot{V}O_{2max}$ or estimates of heart rate (HR) values corresponding to $\dot{V}O_2$ ranges[7]. The minimum relative intensity necessary for aerobic adaptation increases with fitness level, and as such, the recommended intensity for untrained individuals is lower than that for moderately trained and well trained individuals[8].

$\dot{V}O_{2max}$ is often used to track changes in aerobic fitness over the course of a training program[3], as increases in $\dot{V}O_{2max}$ are closely linked to improvements in maximal cardiac output and cellular oxygen extraction from the bloodstream. It should be noted, however, that $\dot{V}O_{2max}$ may stabilize during longer training protocols, with subsequent improvements in performance related to improvements in lactate threshold and/or exercise economy[9]. While this does not necessarily invalidate using $\dot{V}O_{2max}$ to track changes in cardiorespiratory fitness, this decreased sensitivity with prolonged endurance training should be taken into consideration when assessing trained athletes.

Assessment

Laboratory Testing

The most accurate means of measuring $\dot{V}O_{2max}$ is via an incremental exercise test, during which the test subject's pulmonary gases are collected and analyzed. These tests are common in performance lab settings, and demonstrate high construct validity and reliability[10]. During such a test, the intensity that the subject is working against is increased gradually until volitional exhaustion is reached. The test is deemed maximal when a plateau in the rate ventilatory oxygen uptake ($\dot{V}O_2$) is observed despite an increase in workload. This plateau is defined as an increase in $\dot{V}O_2$ above the previous stage’s workload of less than 2.1 mL/kg/min[7]. In the case that that this plateau is not observed, a respiratory exchange ratio (RER) greater than 1.15[7] and/or a HR reading within 10 beats per minute of the subject's age-predicted HR maximum[11] are commonly used as secondary criteria for validating a maximal test.

While secondary criteria may appear to address the problem of subjects not achieving an initial ‘maximal’ result, Poole et al.[11] found using RER > 1.15 underestimated $\dot{V}O_2$max by 16%, and HR criteria tended to exclude subjects that had demonstrated a $\dot{V}O_2$ plateau. Based upon this information, Poole et al.[11] proposed the use of a verification test stage in the absence of a $\dot{V}O_2$ plateau. Briefly, this involves the subject resting for a short period of time, before returning to a workload slightly above the highest workload achieved during the initial test. The use of a verification stage was further investigated by Mier and colleagues[12], who found $\dot{V}O_{2max}$ values during this stage not significantly different than the maximal $\dot{V}O_2$ values produced by subjects that did not plateau at the end of an initial graded exercise test. Taken together, these results support the use of a verification stage in the absence of a $\dot{V}O_2$ plateau, as opposed to using secondary RER or HR criteria.

Field Testing

Cardiovascular fitness is an important component of overall physical fitness across sport, occupational, and general health settings. As such, tests of aerobic performance have been incorporated in fitness testing batteries since 1858[13]. Given that direct $\dot{V}O_{2max}$ determination requires specialized equipment that is either inaccessible or cost prohibitive for most individuals, various field tests have been developed to provide a prediction of $\dot{V}O_{2max}$[14-16]. Moreover, in some team settings, field tests are preferred over direct lab measurement of $\dot{V}O_{2max}$, as coaches may see them as being more specific to the demands of a sport[17]. It is thus important that these tests lend themselves appropriately to repeated measurement, and that both systematic and random error are minimized in the estimate of $\dot{V}O_{2max}$.

Of these, the 12MR is one of the most commonly used field tests due to its simplicity[14], providing a prediction of $\dot{V}O_{2max}$ based upon the maximal distance run in a 12-minute period. This prediction is derived from regression data collected from 115 male US Air Force officers, relating performance in the distance run to the $\dot{V}O_{2max}$ value determined during an incremental treadmill test. While several variations on this protocol exist, ranging in duration from 6 minutes to 15 minutes, and in distance from ¼ mile to 5,000 meters, the 12MR demonstrates one of the strongest correlations with $\dot{V}O_{2max}$[18] (r = 0.78; 95% CI: 0.72, 0.83). Despite it strong correlation however, the 12MR has been shown to overestimate $\dot{V}O_{2max}$ in some aerobically fit individuals[19].

It should also be noted that while $\dot{V}O_{2max}$ is a well established predictor of endurance performance, it is not the only physiological marker strongly correlated with endurance performance. In addition to $\dot{V}O_{2max}$, Joyner & Coyle[20] emphasize the importance of lactate threshold and exercise economy in predicting endurance performance. Anaerobic metabolism may also play a significant role in tasks ranging from 13-30 minutes, contributing up to 10-20% of total ATP turnover[20,21]. As such, the interaction between these factors and $\dot{V}O_{2max}$ may have the potential to influence field test performance, such as that observed in the 12MR.

Intensity – Time Relationship

Background

Despite similarities in $\dot{V}O_{2max}$, individual tolerance to high intensity exercise can vary significantly. To investigate this, Monod & Scherrer first examined the power–time to exhaustion (P–TE) relationship with intermittent isometric contractions[22]. This relationship was found to be inverse and approaches an asymptote at CP during exercise in the severe intensity domain. When applying these observations to whole body dynamic exercise, this same relationship has been observed and investigated extensively in the cycling literature[23,24]. The early advent of the P–TE relationship in cycling is largely attributable to the capability of cycling power meters to directly monitor workload. In activities where power is not easily measured, proxy distance and speed measures have been applied, with similar principles observed as in the cycling power data[25,26]. Given the applicability of the P–TE relationship to modalities utilizing differing metrics and terminology, the remainder of this section will use critical intensity (CI) to describe generalizable concepts, and CS/CP in citing specific examples.

Based upon the relationship described, for a given intensity (I), time to exhaustion (TE) can be estimated by the following equation:

$$TE = W' / (I - CI)$$

As written, W' represents the work that can be performed at intensities greater than CI, while CI is given by the asymptote of the I–TE curve[23,25]. From a purely mathematical standpoint, CI thus represents an intensity that can be maintained for an infinite amount of time without the development of fatigue. The possibility of a speed or workload that can be maintained indefinitely, however, violates basic physiologic principles, and thus TE at CI may be relatively short in practice. While CI has been defined as the highest intensity at which a steady state $\dot{V}O_2$ and blood lactate concentration can be achieved[27], fatigue cannot be solely attributed these measures or to work done above CI. Rather, CI may represent a critical neuromuscular fatigue threshold above which exhaustion is predominantly the result of peripheral mechanisms of fatigue[28,29].

Mechanistic Basis

Critical Power

There may not be a single underlying mechanism that they can be attributed to, with CI and W' determined using performance outcomes as opposed to the measurement of some specific physiologic variable[23]. Early work found constant workload cycling at 5% of maximal aerobic power below CP to elicit a steady state response in $\dot{V}O_2$ and blood lactate concentration ($[La^-]$). Conversely, workloads 5% above CP led to a progressive increase in $[La^-]$ and $\dot{V}O_2$, suggesting that CP represents the highest workload at which physiologic steady state can be achieved[27]. More recently, Vanhatalo et al.[30] expanded upon the protocol used by Poole et al.[27] to produce a more complete profile of metabolic responses above and below CP. Constant load cycling trials were performed at 5% of maximal aerobic power both above (CP+5%) and below (CP-5%) CP. An additional trial was also performed at the same workload as CP-5%, but equal in duration to CP+5% (~12 min; CP+5%$_{\text{isotime}}$). End-exercise levels of phosphocreatine ([PCr]), creatine ([Cr]), [La$^-$], and pH for CP+5% differed from both CP-5% and CP+5%$_{\text{isotime}}$. CP-5% and CP+5%$_{\text{isotime}}$ however, did not differ in any of these variables, suggesting a steady state response below, but not above CP. Vanhatalo et al.[30] also studied biopsies taken from the vastus lateralis muscle of a subset of subjects. This examination found a positive correlation (r = 0.67) between CP and the proportion of type I muscle fibres and a negative correlation (r = -0.76) between CP and the proportion of type IIx muscle fibres, suggesting reliance on predominately oxidative pathways.

The data from Poole et al.[27] and Vanhatalo et al.[30] have distinct limitations – using a range of 10% of maximal aerobic power lacks the precision to discriminate between CP and other threshold markers. They do suggest however, that CP may result from similar underlying mechanisms as maximal lactate steady state (MLSS) and other threshold parameters. While Mattioni Maturana et al.[31] showed CP to overestimate power output at MLSS, work by Kier et al.[32] found CP, MLSS, respiratory compensation point (RCP), and deoxyhemoglobin breakpoint ([HHb]$_{BP}$) to all occur at similar $\dot{V}O_2$ values. Moreover, Bland-Altman analysis showed the bias between CP and each of these parameters to not be different from zero. While the authors do not claim that their data can draw an explicit mechanistic link between CP and these parameters, the work by Poole et al.[27] and Vanhatalo et al.[30] does support this link. Taken collectively, these data support CP being driven by similar, albeit likely not identical, mechanisms as other threshold markers (MLSS, RCP, [HHb]$_{bp}$).

Curvature Constant

The curvature constant of the intensity-time relationship is commonly referred to as a measure of anaerobic work capacity[33,34]. From a mathematical perspective, however, W’ simply represents the amount of work performed (or distance covered) attributable to power outputs or speeds above CI[23]. The magnitude of W’ does not appear to be related to any one muscle fibre type, suggesting a contribution from both oxidative and non-oxidative pathways[30]. As such, it may be an oversimplification to think of W’ mechanistically as strictly a marker of anaerobic metabolism. Still, given the present lack of tools allowing for the direct measurement of anaerobic capacity, W’ may serve as a reasonable proxy[35].

Besides W’, the most common method of estimating anaerobic capacity is the maximal accumulated oxygen deficit (MAOD) method[35]. As workload and oxygen demand at submaximal intensities are linearly related, this method directly measures the difference in observed oxygen consumption and estimated oxygen demand[36]. Unlike MAOD, without direct measurement of underlying physiologic processes, the W’ method’s validity as a measure of anaerobic capacity is contingent upon its relationship with markers of increased non-oxidative metabolic activity. The impact of glycogen levels on the magnitude of W’ lends support to this relationship, as Miura et al.[37] found a decrease in W’ of approximately 20% when subjects were tested in a glycogen depleted state. Moreover, this decrease was accompanied by a reduction in RER and $\dot{V}CO_2$, with no change in peak $\dot{V}O_2$ values, suggesting a greater proportion of oxygen demand was being met through oxidative processes. Muscle [PCr] dynamics during exercise in the severe intensity domain also reflects this relationship, as Rossiter et al.[38] found muscle [PCr] depletion to be closely related to upward drift in $\dot{V}O_2$. While this study did not directly assess W’, exhaustion was ultimately achieved at $\dot{V}O_{2max}$ suggesting complete depletion of W’, and a linear relationship has been established between the $\dot{V}O_2$ slow component and W’[39] ($r^2 = 0.76$). Most recently, a strong positive correlation has been observed between the magnitude of W’ and both end exercise [La$^-$] (r = 0.88) and [Cr] (r = 0.86), while the rate of change in [PCr], [La$^-$], and pH relative to W' depletion remained constant regardless of pacing strategy[30]. While these same data were unable to show a significant relationship between W' and type IIa or IIx muscle fibres, the authors suggest that type I fibres' capacity for ATP resynthesis is an essential factor in the overall size of W'. As such, W' would not be expected to be explicitly linked to a single fibre type.

Influence on Performance

Given the relevance of CP (or CS) and W' to the P-TE relationship, these variables have been investigated with respect to various performance measures. Kolbe et al.[40] examined the relationship between CS and running times for distances ranging from 1-km to 21.1km, observing a moderate correlation (r = -0.75 to -0.85). While these values may lack that sensitivity to accurately predict run times, across distances they were as strong as the correlation between run time and $\dot{V}O_{2max}$ (r = -0.75 to -0.81) In a separate study, where 800-m run time predicted by the CS curve was compared to actual 800-m run performance, similarly strong correlations were found[41] (r = 0.83 to 0.94, with the range of correlation values due to the different models used to determine CS values). When W' was compared to 800-m run speed, no correlation between the two was found (r = -0.07 to 0.23), regardless of the CS model used[42]. These findings may be reconciled by evidence suggesting that training techniques focused on increasing CS, may lead to slight reductions in W'[34,43]. These observations, however, are not statistically significant, and require further investigation. Had increased CS values negatively impacted W', in tasks with a strong reliance on oxidative pathways (i.e. a strong reliance on CS), a weak correlation between W' and overall performance would be expected.

With the bulk of these data supporting CS as an important predictor of performance, Jones et al.[23] suggest that for an individual to achieve optimal endurance performance, the entirety of the task must be performed at or above CS. In this case, the individual running would be expected to run at CS, fully deplete W' at some point, and return to CS for the remainder of the run post-depletion. From this viewpoint, despite the findings of Bosquet et al.[42], W' would be expected to have some positive effect on endurance performance, albeit potentially very small. An interaction between W' and CS could explain these findings, as W' has been shown to have a strong correlation with the difference between race speed and CS in female collegiate distance runners[44] (800m $r^2 = 0.94$, 1600m $r^2 = 0.63$, 5000m $r^2 = 0.99$). Exact race times for these events relative to the CS-TE prediction were not reported in this study, and with the model based purely on a controlled mathematical approach, there is evidence to suggest that strategy described by Jones et al.[23] may not be entirely realistic. While in theory CS represents a fatigueless intensity, several studies have produced results conflicting with this assumption. In elite cyclists, McClave et al.[45] found CP to be sustainable for 14.79 ± 8.38 minutes. Similarly, upon examining moderately trained runners, Bull et al.[46] found CS predictions from various models to be unsustainable across subjects. Only half of their subjects in this case were able to complete a 60-min constant speed trial at the lowest predicted CS value. These findings may in part be explained by recent work that found CP to consistently overestimate maximal lactate steady state[31]. Moreover, gross efficiency has been shown to decline across cycling time trials, which could in turn lead to increased use of anaerobic stores during constant load trials and a subsequent reduction in exercise tolerance[47,48]. Conversely, Smith and Jones[49] found no difference between CS and speed at maximal lactate steady state. While these findings do not show agreement with the current model, they do not necessarily invalidate CI as a predictor of performance. Rather, they suggest that more refined modeling techniques should be considered in future work.

Training Applications

With aerobic adaptation driven by the magnitude and duration of strain placed on the oxygen transport system, for interval training sessions to be effective, athletes and coaches must effectively balance work-recovery ratios[50-53]. Too easy a task will not provide a sufficient stimulus for aerobic adaptation, whereas a too demanding work-recovery balance may result in an athlete fatiguing prematurely[8,52,53]. With the intensity-TE relationship effectively describing an athlete's capacity for work in the severe intensity domain, understanding their W' can allow for prescription of interval training targets that are taxing yet still achievable. Morton & Billat[50] describe a model for determining appropriate recovery intensity and duration wherein the following must be true:

$$(CI - I_r)\, t_r < (I_w - CI)\, t_w$$

In this case, recovery intensity is represented by I_r, recovery duration is represented by t_r, intensity of the interval is represented by I_w, and duration of the interval is represented by t_w. While this model may reasonably predict W' depletion, it assumes a linear reconstitution of W'. With W' at least partially related to [PCr], a curvilinear rate of restoration is more likely[54,55] (Broxterman et al., 2016; Skiba et al., 2012). As such, more recent work has examined the rate of reconstitution of W' based on recovery intensity and duration[55,56] (Skiba et al., 2012; Skiba et al., 2014b). From these data, Skiba et al.[53] (2014a) produced a model to predict the remaining W' balance at any point during intermittent exercise, which has retrospectively been able to identify cases where athletes reported premature exhaustion based on W' balance.

Although the level of precision required by this model may reduce its utility for some athletes, having an approximation of CI may still be beneficial in dictating recovery intervals. The rate of W' reconstitution is largely dependent upon the difference between CP and recovery intensity[55] (Skiba et al., 2012). As such, knowing one's CI can allow athletes to approximate appropriate recovery interval intensities to allow for repeated supra-CI efforts throughout the course of a workout.

CHAPTER 2: THE INFLUENCE OF THE SPEED-TIME RELATIONSHIP ON THE 12-MINUTE RUN TEST FOR MAXIMAL AEROBIC CAPACITY

Abstract

As the most common measure for assessing cardiorespiratory fitness, $\dot{V}O_{2max}$ is used to predict performance in endurance athletes, while in the general population, it is closely associated with mortality, morbidity, and disease risk. With direct lab measurement inaccessible to most individuals, field tests are commonly used to provide a prediction of this value. Moreover, basic physiological principles suggest that factors beyond $\dot{V}O_{2max}$ have a role in driving performance, with the potential to bias field test results. As such, this study assessed the role of the speed-time to exhaustion relationship (i.e. critical speed and W') on performance during a commonly used field test, the Cooper 12-Minute Run (12MR). Thirty individuals (15 male, 15 female) with varied levels of running experience volunteered for and completed this study. Each subject performed the following tests over four visits in a randomized order: one maximal graded treadmill exercise test, six runs to volitional exhaustion (90 seconds – 12 minutes duration, split over two lab visits), and a maximal 12-minute run. Multiple regression analysis was performed with 12MR distance as the dependent variable, while $\dot{V}O_{2max}$ and W' were set as predictor variables. Critical speed (CS) was excluded from this analysis due to its strong correlation with $\dot{V}O_{2max}$. Two Bland-Altman plots examined the limits of agreement between 12MR distance to $\dot{V}O_{2max}$ predicted and critical speed-W' predicted 12MR distance. One-sample t-tests assessed whether the bias between actual 12MR distance and predicted 12MR distances was different from zero. A significant positive correlation was observed between 12MR distance and $\dot{V}O_{2max}$ ($r = 0.888$; $p < 0.05$), but was not statistically significant for W' ($r = 0.160$; $p = 0.845$). Bland-Altman plots showed no apparent bias for either prediction method by distance, but was different from zero ($p < 0.05$) for both $\dot{V}O_{2max}$ (mean difference = -163.52 m) and CS-W' (mean difference = -143.53 m), with wider limits of agreement for $\dot{V}O_{2max}$ than CS-W' (LoA: -819.42 to +492.38 m vs -403.86 to +116.80 m). While these data do not provide additional insight on the cause of variability in 12MR prediction of $\dot{V}O_{2max}$, it supports the use of the 12MR to track improvements in cardiorespiratory fitness over time without concern that performance will be biased by changes in W'. These finding support the link between 12MR performance and aerobic capacity. They may cautiously be interpreted as anaerobic capacity not being linked to 12MR performance, but improvement to the CS-W' model are warranted before confidently using W' as a valid proxy for anaerobic capacity.

Introduction

Maximal aerobic power ($\dot{V}O_{2max}$) is arguably the most common measure used for assessing cardiorespiratory fitness. In the general population, it can classify mortality and disease risk, and is associated with functional capacity[2]. $\dot{V}O_{2max}$, is also a strong predictor of performance in endurance sport, and can be used to track changes in fitness over time[1,3]. Direct measurement of $\dot{V}O_{2max}$ requires specialized equipment operated by trained personnel in a laboratory setting, and can be inaccessible to many individuals, while simply being impractical for larger groups. To combat these limitations, several field testing options have been developed to provide predictions of $\dot{V}O_{2max}$ based on performance of some task. Of these, the maximal distance covered during a 12-minute run (12MR) is commonly used, and has shown the highest criterion-related validity of time-based field tests[4,18].

Field testing presents its own set of challenges, as confounding variables influencing performance must be controlled. It is easy for coaches to ensure athletes are tested in a rested state and when environmental conditions are favorable; however, it is much more challenging to tease out the effect of innate physiologic factors that may also influence performance. While improvements in an athlete's $\dot{V}O_{2max}$ would be expected to translate to improvement across race distances[40], a uniform improvement across distances may not occur with improvements in other physiologic variables. For example, an athlete's anaerobic capacity would be expected to constitute a larger relative contribution to total ATP turnover during shorter events[20], but would provide a relatively small contribution during a marathon. As such, the curvature constant (W') of the speed-time to exhaustion (TE) relationship – a proxy for anaerobic capacity – shows a strong relationship the difference between race speeds and critical speed (CS), with this difference much greater in 1600m runners than 5000m runners[44]. With the 12MR short enough to feasibly be completed in the severe intensity domain, the speed-TE relationship could potentially have a dramatic influence on performance[57]. Moreover, if W' or CS influenced 12MR performance, the predictive validity of 12MR derived $\dot{V}O_{2max}$ would differ based on event distance.

To this end, the purpose of this study was to examine the influence of W' and CS on 12MR performance, and to determine the extent to which CS and W' explain additional variability in 12MR performance beyond that already described by $\dot{V}O_{2max}$. This study also assessed bias in 12MR predication across the range of participant aerobic fitness levels for both the CS-W' model and $\dot{V}O_{2max}$.

Methods

Participants

Thirty-six individuals (20 male, 16 female) volunteered to participate in this study. Four male participants were unable to complete all testing sessions within the designated six-week window, while one male and one female volunteer did not qualify to participate based upon initial health history screening. Data from these individuals have been excluded from this analysis. The remaining participants (n = 30) were aged between 18 and 32 years (average age = 22.0 ± 3.2 years) and all had 1 or fewer risk factors for cardiovascular disease. No participants reported any current or past injury or illness that would prevent them from returning to their pre-injury/illness training volume and/or intensity. All participants reported running at least 3 times for 30 minutes or more during a typical week (average time = 189.2 ± 96.9 total weekly minutes). Twenty-one participants reported regularly engaging in one or more additional modes of endurance exercise beyond running (n = 21; average time = 255.8 ± 164.3 total minutes), while 19 participants reported engaging in some form of resistance exercise (n = 19; average time = 87.7 ± 55.8 total minutes). While all participants had ran on a regular basis, individuals across a range of aerobic fitness levels (male $\dot{V}O_{2max}$ = 54.3 – 73.9 mL/kg/min; female $\dot{V}O_{2max}$ = 37.3 – 56.8 mL/kg/min) and experience levels (2 months – 15 years aerobic training) were invited to participate. Participant demographic characteristics are described in Table 2.1. Prior to testing all participants provided written informed consent and were given the opportunity to ask questions. All screening documents (See Appendices B-D), recruitment materials, and testing procedures were approved by the Oregon State University Institutional Review Board.

Procedures

Each individual participated in four testing sessions – three at the Oregon State University Human Performance Laboratory, and one at a standard 400-meter running track. During the initial visit, participants completed an informed consent form, followed by health and training history questionnaires for initial screening. Participants then had their height and weight measured and their body composition assessed using an InBody 770 multifrequency bioelectrical impedance analysis system (InBody, Cerritos, CA), thereafter followed by their first exercise test for those who met all eligibility requirements. If questionnaire responses were unclear or could affect eligibility status, participants were asked to provide further explanation. When necessary, physician's approval for participation was obtained prior to testing and the initial exercise trial was postponed to a later date. Participants were instructed not to perform structured exercise in the 24 hours prior to testing, and to fast for 2 hours before testing. Over the three lab testing sessions, participants performed one maximal graded exercise test (GXT_{max}) to determine $\dot{V}O_{2max}$, and a series of six runs to exhaustion (split over two visits) to determine critical speed (CS) and the curvature constant of the speed-time relationship. During the visit to the track, participants performed the Cooper 12-minute run test (12MR) to provide a field estimate of $\dot{V}O_{2max}$.

A ParvoMedics TrueMax 2400 metabolic cart was used to assess $\dot{V}O_2$ (ParvoMedics, Sandy, UT). Heart rate (HR) was measured using a Polar HR monitor (Polar, Lake Success, NY). A standard stopwatch (Timex, Waterbury, CT) was used to track time during the time to exhaustion trials and 12MR. All lab tests were conducted on a TrackMaster treadmill (Full Vision, Newton, KS).

During lab testing, temperature and humidity were maintained at comfortable levels (temperature = 22.7 ± 1.4 C; humidity = 35.8 ± 6.0%). Barometric pressure was noted at the beginning of each testing session (755.9 ± 7.2 mmHg), as these data are necessary for flow and gas calibration purposes. All outdoor testing at the track was performed under environmental conditions expected to minimally impact subject performance (temperature = 11.5 ± 3.7 C; wind speed = 2.1 ± 2.7 kph; rainfall = 0.07 ± 0.17 cm)

12-Minute Run: Upon arrival at the track, testing procedures were described to each participant. They were instructed that the goal of the 12MR was to complete as many laps as possible within the 12-minute period. When scheduling of participants of similar speed permitted, testing was performed in small groups of up to three people to encourage maximal effort. It was emphasized that the test was to be completed at a maximal effort, and participants were encouraged to adopt whatever pacing strategy they felt would result in them running the furthest distance. Participants were instructed to run in the inside lane of the track whenever possible to ensure that all distance run during the test would be measured. After instructions were provided, but prior to testing, participants were allowed a period of up to 10-minutes to perform a self-selected warm-up. Dynamic stretching exercises were permitted, but participants were instructed to refrain from any sprinting or high-intensity running. Following the warm-up, participants were given the opportunity to ask any additional questions regarding testing protocol. Following this, testing was initiated, and participants were provided verbal encouragement throughout the duration of the test. Individual timing devices were not permitted during the test, but participants were provided a whistle signal at 3-minute intervals to provide standardized feedback on elapsed time. At the end of the 12-minute period, participants were given a final whistle signal, indicating for them to stop immediately. Their position at the 12-minute point was marked by a test administrator, at which point they were encouraged to walk or run at an easy pace to ensure appropriate cool down. The distance completed for their final lap was determined using a measuring wheel and total distance was recorded. Total distance run was used to predict $\dot{V}O_{2max}$ using the prediction equation derived by Cooper[14].

Maximal Graded Exercise Test: Prior to the GXT_{max}, participants were fitted with a nose clip and mask equipped with two one-way valves connected to the metabolic cart, allowing for the collection of expired gases throughout the test. Based upon prior test performance, starting speed was set between 8.0 to 11.0 kph, with the goal of having the test last between 12 and 15 minutes. If the GXT_{max} was to be performed during a participant's first visit, a self-reported approximation of current running fitness was used. Participants then performed a 3-minute warm-up at a 0% gradient. Following this warm-up, grade was be increased to 3%, signifying the start of the test. Stages were set at 1 minute in duration, with speed or incline increased at the end of each stage. Rating of perceived exertion (RPE) was recorded halfway through each minute[58]. Speed was adjusted first, increasing by 0.8 km/hr at the end of every minute until the participant reached a RPE of 13. From this point, speed was kept constant and incline was increased by 1% grade at the end of each stage until the participant indicates that he/she is unable to continue.

An increase of less than 2.1 mL/kg/min in minute oxygen consumption across the final two stages was taken as criteria for a ‘maximal’ test. If this plateau was achieved, $\dot{V}O_{2max}$ was taken as the maximum minute-average recorded for a completed stage during the test. If a plateau is not achieved, a verification stage was performed following a protocol adapted from Mier et al.[12]. Following a 10-minute active rest period, speed and incline were gradually increased over two minutes to the intensity reached during the final stage of the GXT_{max}. After one minute at this intensity, incline increased by 1% grade, and the participant was vigorously encouraged to maintain this intensity for two minutes. If they maintained at least one minute and the final minute-averaged $\dot{V}O_2$ value measured was within 2.1 mL/kg/min of the maximal value obtained during the initial test, the test was deemed maximal. If the participant completed the verification stage and a plateau in oxygen consumption was not observed, another 10-minute active rest period was allowed, and the verification stage protocol was repeated, but with an increase of 2% grade in the final two minutes. The maximum $\dot{V}O_2$ value recorded during these verification trials will be considered a participant's $\dot{V}O_{2max}$.

CS-W’ Runs to Exhaustion: Six time to exhaustion (TE) trials were conducted over two visits following a protocol similar to that outlined by Hughson et al.[25]. Upon arrival, participants were fitted with a HR monitor and laid supine on a table for a 5-10 minute period for pre-exercise heart rate measurement. They were then allowed a warm up period of up to 10 minutes. Warm up intensity was self-selected, but participants were instructed not to exceed an RPE of 17.

For each trial, treadmill speed was approximated based upon previous test performance and self-reported external run performances. Across the six trials, selected speeds aimed to elicit exhaustion in approximately 1.5-2, 3, 4, 5, 6-8, and 10-12 minutes, with trial order randomized. Each trial began with the participant straddling the treadmill belt as it was increased to the testing speed. Participants then supported themselves using handrails to transfer onto the belt, releasing when they felt they had achieved a balanced stride. Elapsed time started when the handrails were released and ended when they grasped the rails for support. Participants were blinded to elapsed time and speed during all trials, but were told trial length would range from roughly 2 to 12 minutes. Vigorous verbal encouragement was provided throughout all testing.

If subjects reached 12 minutes without achieving volitional fatigue, they were instructed to stop and began the recovery process. These trials were excluded from subsequent analyses. If a subject’s time for any trial was shorter than another one of their trials performed at a faster speed, the trial was assumed to represent a submaximal effort and was also excluded from later analysis. All CS-W’ calculations were performed with a minimum of 4 successful trials.

At the conclusion of each run, participants were given the opportunity to walk for a self-selected period of time, before recovering in a supine position. Heart rate was monitored throughout recovery, and subjects began the subsequent trial when HR returned to within 20 bpm of the pre-exercise level. In the event that a subject’s HR recovery reached a plateau, 3 consecutive readings within a 3 bpm range taken at least 1 minute apart was used as alternate criteria for adequate recovery.

Statistical Analysis

Descriptive Statistics: Mean and standard deviation were calculated for all demographic data (height, weight, age, body fat percentage, relative $\dot{V}O_{2max}$, CS, W’, weekly running time, years of aerobic training experience), as well as for predicted 12MR distance by the CS-W’ model and by $\dot{V}O_{2max}$.

Multiple Regression: Multiple regression analysis was used to examine the relative contributions of $\dot{V}O_{2max}$, CS, and W’ to distance run during 12MR. Given the established relationship between 12MR performance and $\dot{V}O_{2max}$, $\dot{V}O_{2max}$ data were loaded into the model first. A Shapiro-Wilk test was performed to confirm the normality of 12MR distance data. Correlations between predictor variables were examined to check for multicollinearity, and given a strong correlation between $\dot{V}O_{2max}$ and CS, a subsequent multiple regression analysis was performed excluding CS.

Bland-Altman Analysis: Two Bland-Altman plots were constructed to assess the limits of agreement (LoA) between 12MR measured distance (D_{12MR}), and 12MR predicted distance from lab-measured $\dot{V}O_{2max}$ (D_{VO2}) and the CS-W’ relationship ($D_{CSW'}$). In these plots, the difference between measured and predicted distance was plotted on the Y-axis, while the mean of the two values was plotted on the X-axis. $\dot{V}O_{2max}$ predicted distance was based upon the 12MR prediction equation. The CS-W’ model prediction assumed the individual ran the entire 12MR at or above CS with complete depletion of the anaerobic energy stores represented by W’. One-sample t-tests were used to determine whether the average difference between values (i.e. bias) was significantly different from zero.

All analyses were performed using IBM SPSS Statistics 25 (Armonk, NY) and Microsoft Excel (Redmond, WA).

Results

Individual subject measures for D_{12MR}, D_{VO2}, $D_{CSW'}$, $\dot{V}O_{2max}$, CS, and W' are presented in Table 2.2. Multiple regression analysis revealed a significant positive correlation between D_{12MR} and $\dot{V}O_{2max}$ ($r = 0.888$; $p < 0.05$), but was not statistically significant for the relationship between D_{12MR} and W' ($r = 0.160$; $p = 0.845$). Figure 2.1 shows Bland-Altman plots representing D_{12MR}-D_{VO2} agreement and D_{12MR}-$D_{CSW'}$ agreement. The mean difference between D_{12MR} and D_{VO2} (-163.52 m; LoA: -819.42 to +492.38 m) and difference between D_{12MR} and $D_{CSW'}$ (-143.53 m; LoA: -403.86 to +116.80 m) were significantly different ($p < 0.05$) from zero.

Discussion

The main finding of this study was that W' did not contribute significant variability to the distance run during the 12MR ($r = 0.160$; $p = 0.845$). Paired with a strong positive correlation between $\dot{V}O_{2max}$ and D_{12MR} ($r = 0.888$; $p < 0.05$), this lends support to use of the 12MR to track changes in aerobic capacity over time, regardless of any changes in anaerobic capacity that may occur with training.

Interestingly, the lack of correlation between W' and $\dot{V}O_{2max}$ conflicts with Joyner & Coyle's prediction of anaerobic processes contributing to 10-20% of ATP turnover in events of similar duration to the 12MR[20]. With aerobic markers (i.e. $\dot{V}O_{2max}$ and CS) expected to have a relatively large effect size compared to W', a subthreshold effort during any part of the 12MR could potentially mask a contribution to performance from W'. While gas exchange and instantaneous pace data were not collected during the 12MR to confirm a maximal effort, a Bland-Altman plot comparing D_{12MR} to $D_{CSW'}$ showed a mean difference of -143.53m, with D_{12MR} being greater than $D_{CSW'}$ in 25 of the 30 subjects. With $D_{CSW'}$ derived assuming that the subject ran the entirety of the 12MR at or above CS, and W' was completely depleted[23], it is possible that subjects ran portions of the 12MR below their sustainable potential predicted by CS.

The oversimplicity of the CS-W' mathematical model should also be considered, as CS is likely not an acutely static measure. With markers of aerobic metabolism closely linked to CS[30], it may be theoretically sustainable, but the model does not account for an initial delay in $\dot{V}O_2$ response[59,60] or decreases in gross efficiency[47,48]. As such, from the onset of exercise one might expect a 'true' measure of maximal metabolic steady state to start low, track upwards with increases in oxidative phosphorylation, peak for a period, and then ultimately slope downward reflecting decreases in gross efficiency. Further research is required to confirm the effect of these variables on the CS-W' model, but they would be expected to lead to an increased, albeit undetected reliance on anaerobic pathways. In running, for example, W' has been used as a proxy for anaerobic capacity, as it represents the distance covered at speeds greater than CS. However, a disconnect may exist that separates running speed from underlying physiologic processes, which would mask the depletion of anaerobic stores, and thus may overestimate the contribution of aerobic metabolism to running performance.

Regardless of why W' did not appear to factor into 12MR performance, these data fail to uncover factors that may contribute to the wide limits of agreement between D_{12MR} and D_{VO2}, and estimated a mean underperformance on the 12MR of approximately 160 meters. Bland-Altman plots did not appear to indicate any bias based on fitness level. These findings conflict with those of Penry et al.[19], who showed an underprediction of $\dot{V}O_{2max}$ in less aerobically fit individuals and overestimation in fitter individuals. The authors attributed this bias to familiarity with pacing, with their greatest test-retest variability observed in individuals with lower $\dot{V}O_{2max}$ values. While similar feedback was provided in the present study (i.e. subjects blinded to time, but provided signals in 3-minutes intervals), the previous authors state that, "emphasis was placed on pacing oneself throughout the duration of the test". The present subjects were instructed to employ whatever pacing strategy they felt would lead to them covering the greatest distance in the 12-minute period. If this difference in instruction led to a difference in attentional focus or pacing strategies, this could account for differences in 12MR performance[61,62].

While CS data were excluded from multiple regression analysis due to a strong correlation with $\dot{V}O_{2max}$, the D_{12MR}–$D_{CSW'}$ comparison showed narrower limits of agreement than the D_{12MR}–D_{VO2} comparison (LoA: -403.86 to +116.80 m vs. -819.42 to +492.38 m). This suggests that the 12MR may offer a greater degree of precision in approximating the CS-W' model's predicted distance than in approximating $\dot{V}O_{2max}$. Without being able to discriminate between separate components of the CS-W' model however, this is of little practical utility. That said, this relationship could provide a rough approximation of an athlete's CS based upon D_{12MR}, if the test administrator had prior knowledge of the athlete's W'. In this sample of primarily endurance-trained runners and triathletes, W' was 155.6 ± 78.5 m (Table 2.2), which differed drastically from values reported by Jones & Vanhatalo[57] in elite male marathon runners (W' = 328 ± 104 m). As such, between the variability in D_{12MR} relative to $D_{CSW'}$, and the variability of W', athletes and coaches would likely get more accurate estimations of CS by performing a 3-minute all out test[63] or longer time trial[64], so as to minimize over- or underestimating training or racing intensities.

Practical Application

In summary, the CS-W' model does not appear to introduce any additional variability into 12MR performance that is not already captured by $\dot{V}O_{2max}$. Despite this, the 12MR tended to underpredict $\dot{V}O_{2max}$ and demonstrated wide limits of agreement, and thus may not be an appropriate test when a precise measure of $\dot{V}O_{2max}$ is needed. Nonetheless, these data support test administrators' reliable use of the 12MR to track changes in aerobic fitness without concern of results being clouded by changes in anaerobic capacity. This conclusion should be taken with caution, as W' may fail to capture some contributions from anaerobic metabolism. These discrepancies are likely relatively small though, and can in part be attenuated by employing a warm-up protocol prior to testing[65].

Given that our data did not agree with that of Penry et al.[19], it appears that pacing instruction may bias 12MR performance, and such, test administrators should be sure to provide consistent instruction when conducting multiple testing sessions over time. Moreover, an individual's pacing strategy should be monitored in addition to their overall run distance when possible.

Figure 2.1: *Bland-Altman plot comparing 12-minute run distance to* $\dot{V}O_{2max}$ *predicted distance*

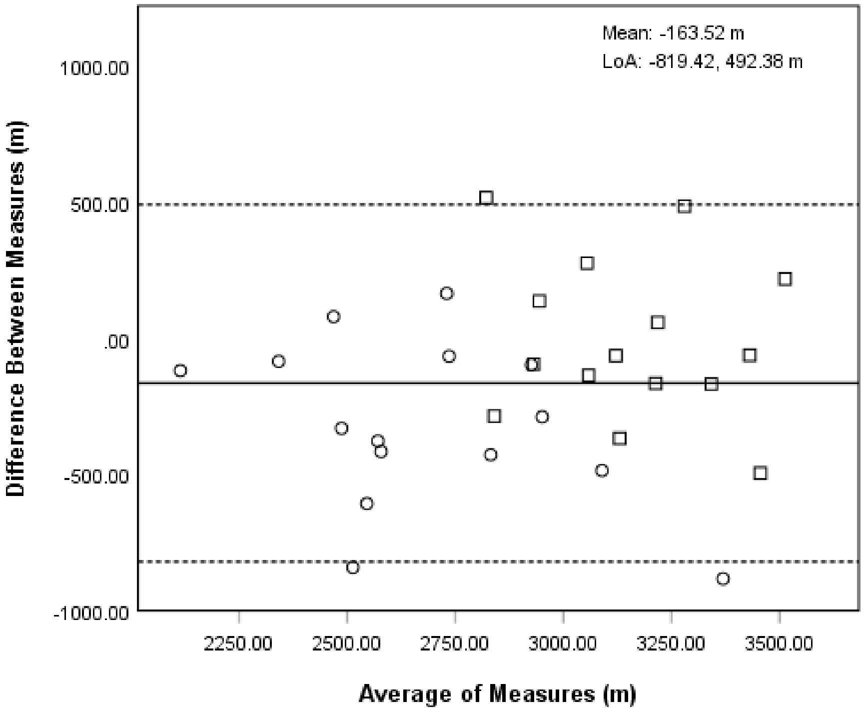

Figure 2.2: *Bland-Altman plot comparing 12-minute run to CS-W' predicted distance*

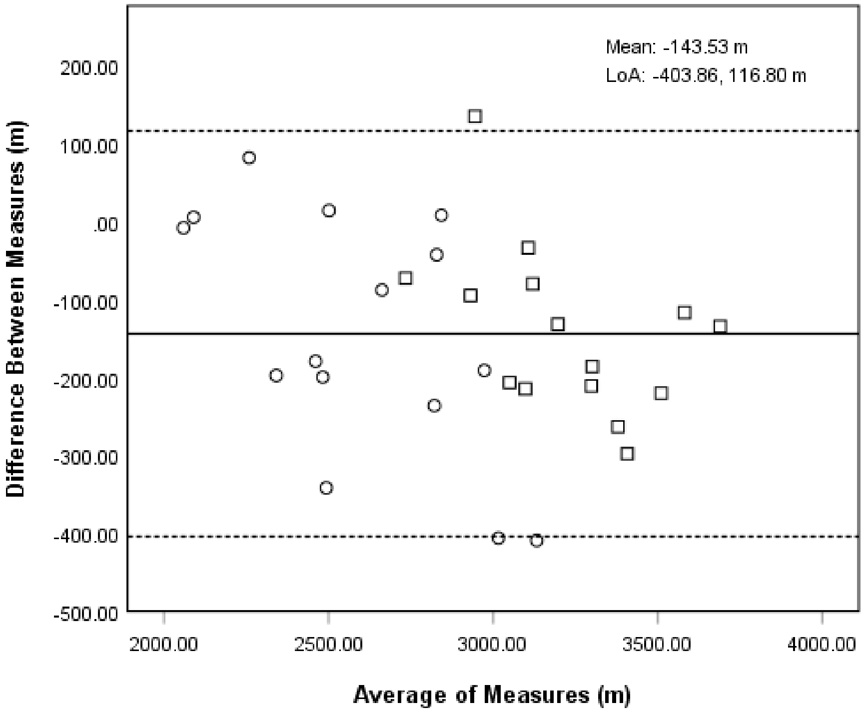

Table 2.1: *Participant demographic data*

	Overall (n = 30) Mean ± SD	Men (n = 15) Mean ± SD	Women (n = 15) Mean ± SD
Age (years)	22.0 ± 3.2	21.9 ± 3.0	22.1 ± 3.7
Height (cm)	173.8 ± 9.6	182.1 ± 4.3	165.5 ± 4.9
Weight (kg)	69.3 ± 10.7	76.9 ± 6.9	61.7 ± 8.0
Body Fat (%)	18.7 ± 7.4	13.7 ± 3.1	23.8 ± 6.9
Aerobic Exercise Experience (years)	4.7 ± 4.0	5.7 ± 3.6	3.8 ± 4.4
Weekly Running Time (min)	189.2 ± 96.9	170.7 ± 75.5	207.8 ± 114.1

Table 2.2: *Participant performance measure data*

Subject	$\dot{V}O_{2max}$ (mL/kg/min)	Critical Speed (m/s)	W' (m)	D_{12MR} (m)	D_{VO2} (m)	$D_{CSW'}$ (m)
1	71.5	4.529	132.8	3208.0	3703.2	3393.6
2	58.6	4.339	81.1	2990.8	3126.1	3205.1
3	50.4	3.341	176.3	2382.6	2759.3	2581.9
4	52.4	3.237	109.4	2242.5	2848.8	2439.7
5	64.8	5.107	79.5	3622.5	3403.5	3756.4
6	50.6	4.063	13.6	2703.2	2768.3	2939.1
7	55.4	3.578	194.0	2697.9	2983.0	2770.0
8	60.0	4.742	96.9	3248.0	3188.8	3511.0
9	55.2	4.139	88.4	2877.6	2974.0	3068.2
10	66.1	4.795	168.4	3400.6	3461.6	3620.6
11	48.0	3.557	102.6	2322.1	2652.0	2663.4
12	42.0	2.870	151.1	2299.6	2383.6	2217.1
13	59.2	4.014	232.9	3090.1	3153.0	3123.2
14	43.0	3.202	189.0	2508.7	2428.3	2494.1
15	62.4	4.132	287.5	3131.1	3296.1	3262.4
16	55.3	3.872	191.0	2884.2	2978.5	2978.5
17	62.8	4.146	168.3	2946.9	3314.0	3153.1
18	54.3	4.049	244.3	3080.3	2933.8	3159.9
19	63.2	4.544	132.0	3193.3	3331.9	3403.8
20	57.9	3.411	421.3	3012.9	3094.8	2877.3
21	53.0	3.834	89.1	2807.1	2875.6	2849.2
22	53.9	3.735	148.8	2846.8	2915.9	2838.2
23	46.0	2.746	109.4	2092.7	2562.5	2086.6
24	47.9	3.612	105.0	2618.3	2647.5	2705.8
25	73.9	4.738	228.0	3523.1	3810.5	3639.5
26	56.6	4.461	125.0	2927.9	3036.7	3336.8
27	56.8	4.381	64.9	2813.1	3045.6	3219.0
28	51.0	3.253	207.4	2370.8	2786.2	2549.7
29	65.3	4.699	172.9	3258.7	3425.8	3556.3
30	37.3	2.648	156.9	2055.4	2173.4	2063.0
Mean ± SD	55.8 ± 8.4	3.926 ± 0.650	155.6 ± 78.5	2838.6 ± 415.1	3002.1 ± 377.3	2982.1 ± 461.6

CHAPTER 3: THE INFLUENCE OF THE SPEED-TIME RELATIONSHIP ON LABORATORY TESTING FOR MAXIMAL AEROBIC CAPACITY

Abstract

Direct laboratory measurement of oxygen consumption ($\dot{V}O_2$) during a maximal graded exercise (GXT_{max}) test remains the gold standard for assessing cardiorespiratory fitness. Nonetheless, many individuals do not achieve a plateau in $\dot{V}O_2$ during traditional testing protocols, resulting in a potential underestimation of maximal oxygen consumption ($\dot{V}O_{2max}$). One possible explanation for this phenomenon is that these individuals may be spending significant amounts of the test in the severe intensity domain, albeit at submaximal intensities. To this end, this study considered the role of high intensity exercise tolerance, examining the relative contributions of critical speed (CS) and the curvature constant of the speed-time to exhaustion relationship (W') on $\dot{V}O_{2max}$ measurement. Thirty individuals (15 male, 15 female) with varied levels of running experience volunteered for and completed this study. Each subject performed one maximal graded treadmill exercise test and six runs to volitional exhaustion (90 seconds – 12 minutes duration) in randomized order over three visits. Multiple regression analysis was performed with $\dot{V}O_{2max}$ as the dependent variable, while CS and W' were set as predictor variables. The relative contributions of both CS and W' was quantified by squared semipartial correlations. Both CS and W' were found to contribute significantly to variance observed in $\dot{V}O_{2max}$ ($sp^2 = 0.803$ and 0.095, respectively; $p < 0.01$), with overall $R^2 = 0.828$. The strong CS-$\dot{V}O_{2max}$ relationship was not unexpected, given that both measures are dependent on aerobic variables such as cardiac output and quantity of type I muscle fibres. The observed W'-$\dot{V}O_{2max}$ relationship may be explained in part by the role of the $\dot{V}O_2$ slow component on W'. Conversely, it is possible that W' may serve a protective role against the deleterious effects of

fatigue inducing metabolites; thus, having a sufficient W’ reserve would allow a subject to continue longer during a GXT_{max}. Overall, these data suggest that measuring an individual’s CS and W’ can serve as a reasonable alternative to $\dot{V}O_{2max}$ when assessing cardiorespiratory fitness. In cases where information on $\dot{V}O_2$ is of specific interest, test administrators may consider altering their protocol when individuals are anticipated to have lower anaerobic capacities. These protocols should ensure sufficient time to allow for $\dot{V}O_2$ to stabilize, but should be designed to avoid overly depleting W’ at submaximal intensities.

Introduction

Maximal aerobic power ($\dot{V}O_{2max}$) is arguably the most common measure used when assessing cardiorespiratory fitness. In the general population, it can classify mortality and disease risk, and is associated with functional capacity[2]. Moreover, $\dot{V}O_{2max}$, is a strong predictor of performance in endurance sport and can be used to track changes in aerobic fitness over time[1,3].

Standard protocols for measuring $\dot{V}O_{2max}$ typically consist of either an incremental (increasing workload at set time intervals) or ramp (continuous increase in workload) maximal graded exercise test (GXT_{max}). Decremental protocols have also been shown to yield similar $\dot{V}O_{2max}$ values[66], but are not used frequently and require multiple testing sessions. During an incremental test, $\dot{V}O_{2max}$ is achieved when an individual, despite increasing workloads, reaches a plateau in minute oxygen consumption ($\dot{V}O_2$). This phenomenon reflects the increased in-test energy demand is being met via non-oxidative metabolic processes. Over the final two stages of the test, the criteria for this plateau is an increase in $\dot{V}O_2$ of less than 2.1 mL/kg/min[7]. It is common however, for individuals to reach volitional fatigue without achieving a plateau, and as such, verification stages or additional criteria for a ‘maximal’ test are commonly used. Nonetheless, these verification stages are often difficult for individuals to complete, and many of the commonly used criteria for a ‘maximal’ test tend to lead to an underprediction of an individual’s true $\dot{V}O_{2max}$[11].

One viable solution to these challenges in assessing $\dot{V}O_{2max}$, is the use of submaximal markers for classifying aerobic fitness. Of these, the critical power (CP) concept may be particularly useful. Critical power has been shown to be positively correlated with proportion of type I muscle fibres[30], and to occur at similar $\dot{V}O_2$ levels as several other threshold markers driven by similar markers of aerobic fitness[20,32,,49]. Moreover, CP and critical speed (CS; for running tasks), and the related curvature constant (W’) component have shown a strong relationship with endurance performance[40,41,44]. It has also been suggested that the power-time relationship may better describe the ability of older adults to perform activities of daily living[67]. Essentially, describing overall capacity in terms of discrete aerobic and anaerobic components (more correctly, high-intensity tolerance) provides a more complete picture of the reliance on different energy systems, and thus factors driving fatigue.

In theory, this model could also predict volitional fatigue during a GXT_{max}. In practice, however, during a ramp protocol, the CP-W’ model overestimates actual performance, with the magnitude of overestimation negatively correlated with W’[68]. While the study authors attribute this discrepancy to $\dot{V}O_2$ kinetics, the negative correlation suggests that W’ may play an important role in testing for $\dot{V}O_{2max}$. As such, and given the potential for CS to be used as surrogate measure of aerobic fitness, the purpose of this study was to investigate the relative contribution of the CS-W’ model to $\dot{V}O_{2max}$ measurement. We hypothesized that both CS and W’ would independently describe a significant proportion of the variability in $\dot{V}O_{2max}$ measurement, with CS accounting for a greater proportion of variability than W’.

Methods

Participants

Thirty-six individuals (20 male, 16 female) volunteered to participate in this study. Four male participants were unable to complete all testing sessions within the designated six-week window, while one male and one female volunteer did not qualify to participate based upon initial health history screening. Data from these individuals have been excluded from this analysis. The remaining participants (n = 30) were aged between 18 and 32 years (average age = 22.0 ± 3.2 years) and all had 1 or fewer risk factors for cardiovascular disease. No participants reported any current or past injury or illness that would prevent them from returning to their pre-injury/illness training volume and/or intensity. All participants reported running at least 3 times for 30 minutes or more during a typical week (average time = 189.2 ± 96.9 total weekly minutes). Twenty-one participants reported regularly engaging in one or more additional modes of endurance exercise beyond running (n = 21; average time = 255.8 ± 164.3 total minutes), while 19 participants reported engaging in some form of resistance exercise (n = 19; average time = 87.7 ± 55.8 total minutes). While all participants had ran on a regular basis, individuals across a range of aerobic fitness levels (male $\dot{V}O_{2max}$ = 54.3 – 73.9 mL/kg/min; female $\dot{V}O_{2max}$ = 37.3 – 56.8 mL/kg/min) and experience levels (2 months – 15 years aerobic training) were invited to participate. Participant demographic characteristics are described in Table 3.1. Prior to testing all participants provided written informed consent and were given the opportunity to ask questions. All screening documents (See Appendices B-D), recruitment materials, and testing procedures were approved by the Oregon State University Institutional Review Board.

Procedures

Each individual participated in three testing sessions at the Oregon State University Human Performance Laboratory. During the initial visit, participants completed an informed consent form, followed by health and training history questionnaires for initial screening. Participants then had their height and weight measured and their body composition assessed using an InBody 770 multifrequency bioelectrical impedance analysis system (InBody, Cerritos, CA), thereafter followed by their first exercise test for those who met all eligibility requirements. If questionnaire responses were unclear or could affect eligibility status, participants were asked to provide further explanation. When necessary, physician's approval for participation was obtained prior to testing and the initial exercise trial was postponed to a later date. Participants were instructed not to perform structured exercise in the 24 hours prior to testing and report to testing at least 2 hours fasted. Over the three testing sessions, participants performed one incremental GXT_{max} to determine $\dot{V}O_{2max}$, and a series of six runs to exhaustion (split over two visits) to determine critical speed (CS) and the curvature constant of the speed-time relationship.

A ParvoMedics TrueMax 2400 metabolic cart was used to assess $\dot{V}O_2$ (ParvoMedics, Sandy, UT). Heart rate (HR) was measured using a Polar HR monitor (Polar, Lake Success, NY). A standard stopwatch (Timex, Waterbury, CT) was used to track time during the time to exhaustion trials. All tests were conducted on a TrackMaster treadmill (Full Vision, Newton, KS).

During testing, lab temperature and humidity were maintained at comfortable levels (temperature = 22.7 ± 1.4 C; humidity = 35.8 ± 6.0%). Barometric pressure was noted at the beginning of each testing session (755.9 ± 7.2 mmHg), as these data are necessary for flow and gas calibration purposes.

Maximal Graded Exercise Test: Prior to the GXT_{max}, participants were fitted with a nose clip and mask equipped with two one-way valves connected to the metabolic cart, allowing for the collection of expired gases throughout the test. Based upon prior test performance starting speed was set between 8.0 to 11.0 kph, with the goal of having the test last between 12 and 15 minutes. If the GXT_{max} was to be performed during a participant's first visit, a self-reported approximation of current running fitness was used. Participants then performed a 3-minute warm-up at a 0% gradient. Following this warm-up, grade was be increased to 3%, signifying the start of the test. Stages were set at 1 minute in duration, with speed or incline increased at the end of each stage. Rating of perceived exertion (RPE) was recorded halfway through each minute (Borg, 1982). Speed was adjusted first, increasing by 0.8 km/hr at the end of every minute until the participant reached a RPE of 13. From this point, speed was kept constant and incline was increased by 1% grade at the end of each stage until the participant indicates that he/she is unable to continue.

An increase of less than 2.1 mL/kg/min in minute oxygen consumption across the final two stages was taken as criteria for a 'maximal' test. If this plateau was achieved, $\dot{V}O_{2max}$ was taken as the maximum minute-average recorded for a completed stage during the test. If a plateau is not achieved, a verification stage was performed following a protocol adapted from Mier et al.[12]. Following a 10-minute active rest period, speed and incline were gradually be increased over two minutes to the intensity reached during the final stage of the GXT_{max}. After one minute at this intensity, incline increased by 1% grade, and the participant was vigorously encouraged to maintain this intensity for two minutes. If they maintained at least one minute and the final minute-averaged $\dot{V}O_2$ value measured was within 2.1 mL/kg/min of the maximal value obtained during the initial test, the test was deemed maximal. If the participant completed the verification stage and a plateau in oxygen consumption was not observed, another 10-minute active rest period was allowed, and the verification stage protocol was be repeated, but with an increase of 2% grade in the final two minutes. The maximum $\dot{V}O_2$ value recorded during these verification trials will be considered a participant's $\dot{V}O_{2max}$.

CS-W' Runs to Exhaustion: Six time to exhaustion (TE) trials were conducted over two visits following a protocol similar to that outlined by Hughson et al. (1984). Upon arrival, participants were fitted with a HR monitor and laid supine on a table for a 5-10 minute period for pre-exercise heart rate measurement. They were then allowed a warm up period of up to 10 minutes. Warm up intensity was self-selected, but participants were instructed not to exceed an RPE of 17.

For each trial, treadmill speed was approximated based upon previous test performance and self-reported external run performances. Across the six trials, selected speeds aimed to elicit exhaustion in approximately 1.5-2, 3, 4, 5, 6-8, and 10-12 minutes, with trial order randomized. Each trial began with the participant straddling the treadmill belt as it was increased to the testing speed. Participants then supported themselves using handrails to transfer onto the belt, releasing when they felt they had achieved a balanced stride. Elapsed time started when the handrails were released and ended when they grasped the rails for support. Participants were blinded to elapsed time and speed during all trials, but were told trial length would range from roughly 2 to 12 minutes. Vigorous verbal encouragement was provided throughout all testing.

If subjects reached 12 minutes without achieving volitional fatigue, they were instructed to stop and began the recovery process. These trials were excluded from subsequent analyses. If a subject's time for any trial was shorter than another one of their trials performed at a faster speed, the trial was assumed to represent a submaximal effort and was also excluded from later analysis. All CS-W' calculations were performed with a minimum of 4 successful trials.

At the conclusion of each run, participants were given the opportunity to walk for a self-selected period of time, before recovering in a supine position. Heart rate was monitored throughout recovery, and subjects began the subsequent trial when HR returned to within 20 bpm of the pre-exercise level. In the event that a subject's HR recovery reached a plateau, 3 consecutive readings within a 3 bpm range taken at least 1 minute apart was used as alternate criteria for adequate recovery.

Statistical Analysis

Descriptive Statistics: Mean and standard deviation were calculated for all demographic data (height, weight, age, body fat percentage, relative $\dot{V}O_{2max}$, CS, W', weekly running time, years of aerobic training experience).

Multiple Regression: Multiple regression analysis was used to examine the relative contributions of CS and W' to $\dot{V}O_{2max}$, quantified by the squared semipartial correlation. A Shapiro-Wilk test was performed to confirm the normality of $\dot{V}O_{2max}$ data. The correlation between CS and W' was examined to confirm that multicollinearity was not present.

All analyses were performed using IBM SPSS Statistics 25 (Armonk, NY) and Microsoft Excel (Redmond, WA).

Results

Individual subject measures for $\dot{V}O_{2max}$, CS, and W' are presented in Table 3.2. Multiple regression analysis revealed significant squared semipartial correlations between CS and $\dot{V}O_{2max}$ ($sr^2 = 0.803$; $p < 0.001$), as well as between W' and $\dot{V}O_{2max}$ ($sr^2 = 0.095$; $p < 0.01$). The overall regression model yielded an R^2 value of 0.828 ($p < 0.001$).

Discussion

CS has been previously shown to be related to other threshold measures such as respiratory compensation point[32] and maximal lactate steady state[32,49]. With these measures driven by similar mechanisms as $\dot{V}O_{2max}$[20,30], the strong observed relationship between CS and

$\dot{V}O_{2max}$ should not come as a surprise. Interestingly, W' also showed a significant effect on $\dot{V}O_{2max}$ measurement, accounting for approximately 10% of the measurement variance.

As W' is typically described as representing an anaerobic reserve component[35], albeit not entirely independent of oxidative processes[30], this relationship may appear to conflict with the traditional notion of $\dot{V}O_{2max}$ as a purely aerobic measure. This discrepancy is likely more an issue of measurement than a phenomenon with a physiological cause. With the intensity at CS and $\dot{V}O_{2max}$ drastically different in many individuals, typical incremental and ramp protocols require individuals to spend a substantial portion of time in the severe-intensity domain. As such, one may be subjected to several minutes of W' depletion before reaching an intensity high enough to elicit a $\dot{V}O_2$ plateau. In this sense, a larger W' appears to have a protective effect against the increasing hydrogen ion and inorganic phosphate concentrations that drive muscular fatigue. Conversely, a small W' may limit the ability to access one's complete aerobic capacity, with observed $\dot{V}O_{2peak}$ values falling in some middle area between CS and their true $\dot{V}O_{2max}$.

Given the overall strength of the multiple regression model, testing for CS and W' appears a reasonable alternative for assessing maximal aerobic power. While this may lack the precision to discriminate subtle variations in $\dot{V}O_{2max}$, in most cases, the practical benefit of having information on high intensity tolerance likely outweighs these small differences. If a precise $\dot{V}O_{2max}$ measurement is warranted, test administrators should consider adjusting GXT_{max} protocols being used based upon their subject population. If a prior approximation of $\dot{V}O_{2max}$ is available, decremental protocols[66] may be particularly useful in individuals where a lower anaerobic capacity is anticipated. While W' depletion would still occur, it would not be wasted completing stages at submaximal intensities. Alternatively, an incremental protocol using unequal intensity increases above threshold, while narrowing increases approaching $\dot{V}O_{2max}$ may offer a similar benefit, although to our knowledge has not presently been validated.

It should be noted that given the multifaceted nature of W', these data cannot unequivocally confirm that anaerobic capacity is what is affecting $\dot{V}O_{2max}$ measurement. While W' has been linked to several markers of non-oxidative metabolism[30,37,38], it does not directly relate to type II muscle fibre proportion[30]. It does however, exhibit a strong relationship with the magnitude of the $\dot{V}O_2$ slow component[39], suggesting that the oxidative component of W' is primarily driven by ATP resynthesis in response to phosphocreatine depletion[30,38]. As such, these data cannot necessarily differentiate whether the effect of W' on $\dot{V}O_{2max}$ is the result of the $\dot{V}O_2$ slow component or simply completing greater workloads before reaching fatigue.

Future research should consider the influence of maximal accumulated oxygen deficit (MAOD)[36] on $\dot{V}O_{2max}$ measurement. Along with W', MAOD is a commonly used technique for assessing anaerobic capacity[35] in absence of a direct measurement tool. When accounting for work demand not met by oxygen consumption, MAOD may provide more definitive information on whether anaerobic processes are directly influencing $\dot{V}O_{2max}$. Moreover, as MAOD may be determined from gas exchange data collected during a traditional GXT_{max}, it has the potential to be used in conjunction with $\dot{V}O_{2peak}$ to determine $\dot{V}O_{2max}$. Such a methodology could eliminate the need for challenging verification stages to confirm a maximal value.

Practical Application

In summary, W' appears to play a significant role in testing for $\dot{V}O_{2max}$ using a traditional GXT_{max} protocol. This, paired with a strong relation between CS and $\dot{V}O_{2max}$, indicates that the CS-W' relationship may be a valid proxy for assessing cardiorespiratory fitness. Additionally, the CS-W' relationship provides the benefit of giving test administrators insight on an individuals anaerobic capacity and high intensity exercise tolerance.

In the event that specific information on an individual's $\dot{V}O_2$ response is desired, these findings support adjusting traditional GXT_{max} protocols to fit the capacity of the individual being tested. In individuals whose W' values are anticipated to be lower in magnitude, as may be approximated by previous performances or training history, this likely means spending as little time at suprathreshold, submaximal intensities as possible. This may be achieved by adopting non-traditional testing protocols (i.e. decremental) or by adjusting the magnitude of increases in workload being used at different relative intensities.

Table 3.1: *Participant demographic data*

	Overall (n = 30) Mean ± SD	Men (n = 15) Mean ± SD	Women (n = 15) Mean ± SD
Age (years)	22.0 ± 3.2	21.9 ± 3.0	22.1 ± 3.7
Height (cm)	173.8 ± 9.6	182.1 ± 4.3	165.5 ± 4.9
Weight (kg)	69.3 ± 10.7	76.9 ± 6.9	61.7 ± 8.0
Body Fat (%)	18.7 ± 7.4	13.7 ± 3.1	23.8 ± 6.9
Aerobic Exercise Experience (years)	4.7 ± 4.0	5.7 ± 3.6	3.8 ± 4.4
Weekly Running Time (min)	189.2 ± 96.9	170.7 ± 75.5	207.8 ± 114.1

Table 3.2: *Participant performance measure data*

Subject	$\dot{V}O_{2max}$ (mL/kg/min)	Critical Speed (m/s)	W' (m)
1	71.5	4.529	132.8
2	58.6	4.339	81.1
3	50.4	3.341	176.3
4	52.4	3.237	109.4
5	64.8	5.107	79.5
6	50.6	4.063	13.6
7	55.4	3.578	194.0
8	60.0	4.742	96.9
9	55.2	4.139	88.4
10	66.1	4.795	168.4
11	48.0	3.557	102.6
12	42.0	2.870	151.1
13	59.2	4.014	232.9
14	43.0	3.202	189.0
15	62.4	4.132	287.5
16	55.3	3.872	191.0
17	62.8	4.146	168.3
18	54.3	4.049	244.3
19	63.2	4.544	132.0
20	57.9	3.411	421.3
21	53.0	3.834	89.1
22	53.9	3.735	148.8
23	46.0	2.746	109.4
24	47.9	3.612	105.0
25	73.9	4.738	228.0
26	56.6	4.461	125.0
27	56.8	4.381	64.9
28	51.0	3.253	207.4
29	65.3	4.699	172.9
30	37.3	2.648	156.9
Mean ± SD	55.8 ± 8.4	3.926 ± 0.650	155.6 ± 78.5

REFERENCES

1. Mclaughlin JE, Howley ET, Bassett DR, Thompson DL, Fitzhugh EC. Test of the Classic Model for Predicting Endurance Running Performance. Medicine & Science in Sports & Exercise. 2010 May 1;42(5):991–7.

2. Shephard RJ. Maximal oxygen intake and independence in old age. British Journal of Sports Medicine. 2009 May 1;43(5):342–6.

3. Jones AM, Carter H. The effect of endurance training on parameters of aerobic fitness. Sports Med. 2000 Jun;29(6):373–86.

4. Brooks GA, Fahey TD, White TP. Exercise physiology: human bioenergetics and its pplications [Internet]. London: McGraw-Hill Education; 2005. Available from: http://www.tandfonline.com/toc/rwhi20/

5. Saltin B, Calbet JAL. Point: in health and in a normoxic environment, VO2 max is limited primarily by cardiac output and locomotor muscle blood flow. J Appl Physiol. 2006;100(2):744–5.

6. Wagner PD. Counterpoint: in health and in a normoxic environment, VO2 max is limited primarily by cardiac output and locomotor muscle blood flow. J Appl Physiol. 2006;100(2):745–7

7. American College of Sports Medicine, Riebe D, Ehrman JK, Liguori G, Magal M. ACSM’s guidelines for exercise testing and prescription. 2018.

8. Garber CE, Blissmer B, Deschenes MR, Franklin BA, Lamonte MJ, Lee I-M, et al. American College of Sports Medicine position stand. Quantity and quality of exercise for developing and maintaining cardiorespiratory, musculoskeletal, and neuromotor fitness in apparently healthy adults: guidance for prescribing exercise. Med Sci Sports Exerc. 2011 Jul;43(7):1334–59.

9. Martin DE, Vroon DH, May DF, Pilbeam SP. Physiological Changes in Elite Male Distance Runners Training for Olympic Competition. Phys Sportsmed. 1986 Jan;14(1):152–206.

10. Thoden JS. Physiological Testing of the High-Performance Athlete. Champaign, IL: Human Kinetics; 1990. Testing Aerobic Power; p. 107–174.

11. Poole DC, Wilkerson DP, Jones AM. Validity of criteria for establishing maximal O2 uptake during ramp exercise tests. Eur J Appl Physiol. 2008 Mar 1;102(4):403–10.

12. Mier CM, Alexander RP, Mageean AL. Achievement of V̇O2max Criteria During a Continuous Graded Exercise Test and a Verification Stage Performed by College Athletes. Journal of Strength and Conditioning Research. 2012 Oct 1;26(10):2648–54.

13. Knapik JJ, East WB. History of United States Army physical fitness and physical readiness training. US Army Med Dep J. 2014 Jun;5–19.

14. Cooper KH. A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. JAMA. 1968 Jan 15;203(3):201–4.

15. Léger L, Boucher R. An indirect continuous running multistage field test: the Université de Montréal track test. Can J Appl Sport Sci. 1980 Jun;5(2):77–84.

16. Léger LA, Lambert J. A maximal multistage 20-m shuttle run test to predict VO2 max. Eur J Appl Physiol Occup Physiol. 1982;49(1):1–12.

17. Jemni M, Prince MS, Baker JS. Assessing Cardiorespiratory Fitness of Soccer Players: Is Test Specificity the Issue?-A Review. Sports Med Open. 2018 Jun 19;4(1):28.

18. Mayorga-Vega D, Bocanegra-Parrilla R, Ornelas M, Viciana J. Criterion-Related Validity of the Distance- and Time-Based Walk/Run Field Tests for Estimating Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis. PLOS ONE. 2016 Mar 17;11(3):e0151671.

19. Penry JT, Wilcox AR, Yun J. Validity and reliability analysis of Cooper's 12-minute run and the multistage shuttle run in healthy adults. J Strength Cond Res. 2011 Mar;25(3):597–605.

20. Joyner MJ, Coyle EF. Endurance exercise performance: the physiology of champions. J Physiol (Lond). 2008 Jan 1;586(1):35–44.

21. Bangsbo J, Michalsik L, Petersen A. Accumulated O2 deficit during intense exercise and muscle characteristics of elite athletes. Int J Sports Med. 1993 May;14(4):207–13.

22. Monod H, Scherrer J. The Work Capacity of a Synergic Muscular Group. Ergonomics. 1965 Jul 1;8(3):329–38.

23. Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical Power: Implications for Determination of $\dot{V}$O2max and Exercise Tolerance. Medicine & Science in Sports & Exercise. 2010 Oct 1;42(10):1876–90.

24. Moritani T, Nagata A, Devries HA, Muro M. Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics. 1981 May 1;24(5):339–50.

25. Hughson RL, Orok CJ, Staudt LE. A High Velocity Treadmill Running Test to Assess Endurance Running Potential. Int J Sports Med. 1984 Feb;05(01):23–5.

26. Wakayoshi K, Yoshida T, Kasai T, Moritani T, Mutoh Y, Miyashita M. Validity of critical velocity as swimming fatigue threshold in the competitive swimmer. Ann Physiol Anthropol. 1992 May;11(3):301–7.

27. Poole DC, Ward SA, Gardner GW, Whipp BJ. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. Ergonomics. 1988 Sep 1;31(9):1265–79.

28. Burnley M, Vanhatalo A, Jones AM. Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. J Appl Physiol. 2012 Jul;113(2):215–23.

29. Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM. Critical Power: An Important Fatigue Threshold in Exercise Physiology. Medicine & Science in Sports & Exercise. 2016 Nov 1;48(11):2320–34.

30. Vanhatalo A, Black MI, DiMenna FJ, Blackwell JR, Schmidt JF, Thompson C, et al. The mechanistic bases of the power–time relationship: muscle metabolic responses and relationships to muscle fibre type. The Journal of Physiology. 2016 Aug 1;594(15):4407–23.

31. Mattioni Maturana F, Keir DA, McLay KM, Murias JM. Can measures of critical power precisely estimate the maximal metabolic steady-state? Appl Physiol Nutr Metab. 2016 Aug 16;41(11):1197–203.

32. Keir DA, Fontana FY, Robertson TC, Murias JM, Paterson DH, Kowalchuk JM, et al. Exercise Intensity Thresholds: Identifying the Boundaries of Sustainable Performance. Med Sci Sports Exerc. 2015 Sep;47(9):1932–40.

33. Green S, Dawson BT, Goodman C, Carey MF. Y-intercept of the maximal work-duration relationship and anaerobic capacity in cyclists. Eur J Appl Physiol Occup Physiol. 1994;69(6):550–6.

34. Jenkins DG, Quigley BM. The y-intercept of the critical power function as a measure of anaerobic work capacity. Ergonomics. 1991 Jan;34(1):13–22.

35. Noordhof DA, Skiba PF, de Koning JJ. Determining anaerobic capacity in sporting activities. Int J Sports Physiol Perform. 2013 Sep;8(5):475–82.

36. Medbø JI, Mohn AC, Tabata I, Bahr R, Vaage O, Sejersted OM. Anaerobic capacity determined by maximal accumulated O2 deficit. J Appl Physiol. 1988 Jan;64(1):50–60.

37. Miura A, Sato H, Sato H, Whipp BJ, Fukuba Y. The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. Ergonomics. 2000 Jan;43(1):133–41.

38. Rossiter HB, Ward SA, Kowalchuk JM, Howe FA, Griffiths JR, Whipp BJ. Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on- and off-transients of moderate- and high-intensity exercise in humans. The Journal of Physiology. 2002 Jun 1;541(3):991–1002.

39. Murgatroyd SR, Ferguson C, Ward SA, Whipp BJ, Rossiter HB. Pulmonary O2 uptake kinetics as a determinant of high-intensity exercise tolerance in humans. J Appl Physiol. 2011 Jun;110(6):1598–606.

40. Kolbe T, Dennis SC, Selley E, Noakes TD, Lambert MI. The relationship between critical power and running performance. J Sports Sci. 1995 Jun;13(3):265–9.

41. Bosquet L, Duchene A, Lecot F, Dupont G, Leger L. Vmax estimate from three-parameter critical velocity models: validity and impact on 800 m running performance prediction. Eur J Appl Physiol. 2006 May;97(1):34–42.

42. Bosquet L, Delhors PR, Duchene A, Dupont G, Leger L. Anaerobic Running Capacity Determined from a 3-Parameter Systems Model: Relationship with other Anaerobic Indices and with Running Performance in the 800 m-Run. Int J Sports Med. 2007 Jun;28(06):495–500.

43. Vanhatalo A, Doust JH, Burnley M. A 3-min All-out Cycling Test Is Sensitive to a Change in Critical Power. Medicine & Science in Sports & Exercise. 2008 Sep 1;40(9):1693–9.

44. Pettitt RW, Jamnick N, Clark IE. 3-min all-out exercise test for running. Int J Sports Med. 2012 Jun;33(6):426–31.

45. McClave SA, LeBlanc M, Hawkins SA. Sustainability of critical power determined by a 3-minute all-out test in elite cyclists. J Strength Cond Res. 2011 Nov;25(11):3093–8.

46. Bull AJ, Housh TJ, Johnson GO, Rana SR. Physiological responses at five estimates of critical velocity. Eur J Appl Physiol. 2008 Apr;102(6):711–20.

47. Mulder RC, Noordhof DA, Malterer KR, Foster C, de Koning JJ. Anaerobic work calculated in cycling time trials of different length. Int J Sports Physiol Perform. 2015 Mar;10(2):153–9.

48. Noordhof DA, Mulder RC, Malterer KR, Foster C, de Koning JJ. The decline in gross efficiency in relation to cycling time-trial length. Int J Sports Physiol Perform. 2015 Jan;10(1):64–70.

49. Smith CG, Jones AM. The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. Eur J Appl Physiol. 2001 Jul;85(1–2):19–26.

50. Morton RH, Billat LV. The critical power model for intermittent exercise. Eur J Appl Physiol. 2004 Mar;91(2–3):303–7.

51. Margaria R, Oliva RD, Di Prampero PE, Cerretelli P. Energy utilization in intermittent exercise of supramaximal intensity. J Appl Physiol. 1969 Jun;26(6):752–6.

52. Saltin B, Essén B, Pedersen PK. Intermittent Exercise: its Physiology and some Practical Applications. Advances in Exercise Physiology. 1976;9:23–51.

53. Skiba PF, Clarke D, Vanhatalo A, Jones AM. Validation of a novel intermittent w' model for cycling using field data. Int J Sports Physiol Perform. 2014 Nov;9(6):900–4.

54. Broxterman RM, Skiba PF, Craig JC, Wilcox SL, Ade CJ, Barstow TJ. W' expenditure and reconstitution during severe intensity constant power exercise: mechanistic insight into the determinants of W'. Physiol Rep. 2016;4(19).

55. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and reconstitution of work capacity above critical power. Med Sci Sports Exerc. 2012 Aug;44(8):1526–32.

56. Skiba PF, Chidnok W, Vanhatalo A, Jones AM. Modeling the expenditure and reconstitution of work capacity above critical power. Med Sci Sports Exerc. 2012 Aug;44(8):1526–32.

57. Jones AM, Vanhatalo A. The 'Critical Power' Concept: Applications to Sports Performance with a Focus on Intermittent High-Intensity Exercise. Sports Med. 2017;47(Suppl 1):65–78.

58. Borg GA. Psychophysical bases of perceived exertion. Med Sci Sports Exerc. 1982;14(5):377–81.

59. Grassi B, Poole DC, Richardson RS, Knight DR, Erickson BK, Wagner PD. Muscle O2 uptake kinetics in humans: implications for metabolic control. J Appl Physiol. 1996 Mar;80(3):988–98.

60. Whipp BJ, Wasserman K. Oxygen uptake kinetics for various intensities of constant-load work. J Appl Physiol. 1972 Sep;33(3):351–6.

61. Brick NE, Campbell MJ, Metcalfe RS, Mair JL, Macintyre TE. Altering Pace Control and Pace Regulation: Attentional Focus Effects during Running. Med Sci Sports Exerc. 2016 May;48(5):879–86.

62. de Koning JJ, Foster C, Bakkum A, Kloppenburg S, Thiel C, Joseph T, et al. Regulation of Pacing Strategy during Athletic Competition. PLoS One. 2011 Jan;6(1): e15863.

63. Broxterman RM, Ade CJ, Poole DC, Harms CA, Barstow TJ. A single test for the determination of parameters of the speed-time relationship for running. Respir Physiol Neurobiol. 2013 Jan 15;185(2):380–5.

64. Mattioni Maturana F, Keir DA, McLay KM, Murias JM. Critical power testing or self-selected cycling: Which one is the best predictor of maximal metabolic steady-state? J Sci Med Sport. 2017 Aug;20(8):795–9.

65. Wittekind AL, Beneke R. Effect of warm-up on run time to exhaustion. J Sci Med Sport. 2009 Jul;12(4):480–4.

66. Taylor K, Seegmiller J, Vella CA. The Decremental Protocol as an Alternative Protocol to Measure Maximal Oxygen Consumption in Athletes. Int J Sports Physiol Perform. 2016 Nov;11(8):1094–9.

67. Neder JA, Jones PW, Nery LE, Whipp BJ. The effect of age on the power/duration relationship and the intensity-domain limits in sedentary men. Eur J Appl Physiol. 2000 Jul;82(4):326–32.

68. Black MI, Jones AM, Kelly JA, Bailey SJ, Vanhatalo A. The constant work rate critical power protocol overestimates ramp incremental exercise performance. Eur J Appl Physiol. 2016;116(11):2415–22.

APPENDIX A: IRB PROTOCOL

RESEARCH PROTOCOL

10/12/17

1. Protocol Title: "**Addressing Error in the Cooper 12-Minute Run: The Influence of Exercise Tolerance Parameters"**

PERSONNEL

2. Principal Investigator: Jason Penry PhD (Senior Instructor KIN; Director Human Performance Laboratory)
3. Student Researcher(s): Aaron Seipel (MS Student), Morgan Anderson (MS Student), Stephanie Baxter (Undergraduate Student), Micah White (Undergraduate Student), Arthur Chan (Undergraduate Student)

4. Investigator Qualifications

Below find the qualifications of each of the research team members, who have professional degrees, and experience in working with human subjects and patients. Collectively they have more than twenty years of experience in the areas of exercise science and exercise testing. As such, they are very qualified to work with human subjects and address unforeseen issues if they arise. Research papers and curriculum vitas are available on request to verify the experience and expertise of this research team.

Dr. J. Penry has a PhD in Exercise and Sport Science and is the Director of the Oregon State University Human Performance Laboratory. Over the course of his career, he has independently administered hundreds of VO_{2max} tests, as well as actively participated in many such tests himself. His research experience includes work specific to VO_{2max} and critical speed testing, including repeated testing of study participants and comparison of field and laboratory test methodologies. As a result of the EMT-B certification that he held in North Carolina, he is trained in emergency procedures that may arise in the performance lab. A former Division I collegiate distance runner and current competitive cyclist, Dr. Penry is also familiar with many of the practical aspects associated with maximal aerobic testing and endurance sport performance. Dr. Penry has trained all student researchers to obtain informed consent and perform exercise testing and interpretation procedures specific to this research question, through both independent study and as part of a quarter-long seminar series for graduate students interested in human performance. Based on his professional training and experience, Dr. Penry is capable of overseeing this project and supervising the students involved in the proposed project.

Mr. A. Seipel is completing his MS degree in Kinesiology and currently holds an undergraduate degree in Exercise and Sport Science. During his time as an undergraduate, he assisted with research in the Oregon State Human Performance Lab, helping conduct $\dot{V}O_2$max tests and administering cycling time-trials in 50 subjects. Mr. Seipel has performed further maximal testing with members of the general public, and has taught maximal and submaximal testing protocols to undergraduate students in Exercise Physiology and Fitness Assessment courses. Overall, he has performed and overseen over 100 maximal graded exercise tests, in addition to having participated in several of these tests himself. Moreover, he has been extensively trained in body composition assessment, as is necessary for this study. In addition to his experience conducting exercise tests, Dr. Penry has trained Mr. Seipel to appropriately respond to emergencies in the lab. He also gained experience responding to sudden cardiac incidents in working as a lifeguard at Dixon Recreation Center for over 4 years. Taken collectively, these experiences demonstrate Mr. Seipel's capability to work with human subjects, protect confidentiality, and conduct maximal exercise testing. In addition, he is also an experienced triathlete and runner and has taught running courses in the physical activity program at Oregon State. Having raced triathlons and running events for the past 8 years, Mr. Seipel is very familiar with the population being tested in this study. He will work closely with Dr. Penry and the other members of the research team for all aspects of this research project, and will be using the data collected to complete his MS thesis.

Ms. M. Anderson is completing her MS degree in Kinesiology and currently holds an undergraduate degree in Kinesiology. During her time as an undergraduate, and continuing as a master's student, she has helped conduct numerous VO_2max tests of members of the general public and taught VO_2max testing protocols to undergraduate students in the Oregon State Human Performance Laboratory in Exercise Physiology Lab Methods courses. She has also been trained in body composition assessments, as is necessary for this study. Ms. Anderson is certified in CPR and First Aid as well as trained in emergency laboratory procedures. With these experiences, Ms. Anderson has demonstrated aptitude for working with human subjects, protecting confidentiality, and performing maximal exercise testing. Also, as a current Division I collegiate distance runner, Ms. Anderson is familiar with the population being tested for this study. She will work closely with Dr. Penry, Mr. Seipel, and other members of the research team for all aspects for this research project.

Mrs. S. Burleson is completing her bachelor's degree in Kinesiology. She is currently working at Pinnacle Physical Therapy where she leads patients through therapist-prescribed exercises, encouraging them as needed. She has performed VO_2max testing in the Oregon State Performance Lab and sub-maximal cycle ergometer testing as part of her Kinesiology coursework. Mrs. Burleson has experience working with human subjects, keeping confidentiality, and basic first aid. Also, she is an avid runner and thusly has experience with the test population. She will be working closely with Dr. Penry, Mr. Seipel, and the rest of the research team to gather data for this research study.

Mr. M. White is completing his bachelor's degree in Kinesiology. He has completed coursework in Exercise Physiology and Fitness Assessment. He also has practical experience specific to distance running as a competitive middle distance runner. He will be working closely with Dr. Penry, Mr. Seipel, and the rest of the research team to gather data for this research study.

Mr. A. Chan recently completed his bachelor's degree in Kinesiology. He has completed coursework in Exercise Physiology and Fitness Assessment, during which he gained experience with VO_2max testing and conducting submaximal graded cycle ergometer tests. He will be working closely with Dr. Penry, Mr. Seipel, and the rest of the research team to gather data for this research study.

5. Training and Oversight

Dr. Penry will be responsible for the oversight of the study staff, including supervising the student researchers. He will meet with student researchers frequently throughout the study, typically daily during the period of subject recruitment and testing. He will review all participant data with student researchers to assure all issues are addressed, should they arise. He will also be responsible for ensuring the study ream possesses the necessary skills related to exercise test supervision, for all human subject protections issues, and for the timely and complete submissions of IRB related documents.

All study staff have been sufficiently trained and practiced in the techniques and methods required for this study, including but not limited to, maximal graded exercise and $\dot{V}O_2$max testing, critical speed testing, and administration of questionnaires. Dr. Penry will work closely with A. Seipel and the rest of the research team to assure VO_{2max} testing equipment is functioning properly. Dr. Penry will oversee $\dot{V}O_2$max assessments. Study team members are already trained on VO_2max assessments. Dr. Penry has been doing VO_{2max} assessments in the OSU Human Performance Laboratory over the past 11 years, and maximal testing has been performed in this lab since the 1980s.

FUNDING

6. Sources of Support for this project (unfunded, pending, or awarded)

This research study is funded via the Oregon State University Human Performance Laboratory. It is not externally funded.

DESCRIPTION OF RESEARCH

7. Description of Research

The objective of this study is to examine the extent to which critical speed (CS) and the severe domain distance capacity (W’) predict performance on the Cooper 12-minute run test (12MR) relative to $\dot{V}O_2$max. The 12MR is commonly used to predict $\dot{V}O_2$max based the distance an individual can run in a 12-minute period. This prediction does not factor in any influence of other physiological variables know to be correlated with endurance performance. As such, it is possible that the observed 12MR-$\dot{V}O_2$max relationship is the result of interaction between $\dot{V}O_2$max and other strong predictors of endurance performance. This research is intended to fulfill the requirements for a Masters thesis and will ultimately be published in a peer-reviewed journal.

Aim #1: Examine the role of CS, $\dot{V}O_2$max, and W’ in predicting 12MR performance. We hypothesize that all of these variables will show a direct and positive correlation with 12MR performance. It is hypothesized that CS and $\dot{V}O_2$max will show a stronger relationship with 12MR performance than W’.

Aim #2: Assess interaction effects between CS, $\dot{V}O_2$max, and W’ and how these effects may account for 12MR performance. We hypothesize that the variability in 12MR performance accounted for by $\dot{V}O_2$max will largely be the result of a $\dot{V}O_2$max-CS interaction. It is also hypothesized that there may be a W’-CS interaction, but we expect this to be independent of 12MR variability atributable to W’.

To achieve these aims, CS and W’ will be determined through a series of six treadmill runs to volitional fatigue, $\dot{V}O_2$max will be determined via a maximal graded exercise test, and the 12MR will be performed on an outdoor running track. Using stepwise multiple regression analysis the CS-, W’-, and $\dot{V}O_2$max-12MR relationships will be assessed, and interactions between CS, W’, and $\dot{V}O_2$max will be noted.

This research will be used for the thesis of master’s student, Aaron Seipel. We plan to submit the research for publication in Medicine and Science in Sports and Exercise Journal (MSSE), or the Journal of Strength and Conditioning Research (JSCR). We will submit an abstract for presentation at the American College of Sports Medicine (ACSM) Annual Meeting.

8. Background Justification

In assessing an individual’s cardiorespiratory fitness, maximal rate of oxygen consumption, $\dot{V}O_2$max, is arguably the most common measure used. $\dot{V}O_2$max is throught to be a strong predictor of endurance performance and functional capacity (McLaughlin et al., 2010; Shephard, 2008), and thus can be used to track changes over time (Jones & Carter, 2000). The gold standard determination of $\dot{V}O_2$max requires specialized equipment that is used to collect and analyze pulmonary gases in a laboratory setting during an incremental test. This makes direct $\dot{V}O_2$max measurement inaccessible to many individuals. As such, various field tests have been developed that are easy to administer and provide predictions of $\dot{V}O_2$max.

Of the field tests for $\dot{V}O_2$max prediction, the 12MR (Cooper, 1968) is one of the most commonly used. The test assumes a maximal effort and provides a prediction of $\dot{V}O_2$max based upon the distance an individual is able to run in a 12-minute period. This prediction is derived from regression data collected from 115 male US Air Force officers whose distance run was related to $\dot{V}O_2$max determined using an incremental test. In a recent meta-analysis of run/walk field tests, Mayorga-Vega and colleagues (2016) assessed criterion-related validity of the 12MR using a Pearson's zero-order correlation coefficient (*r*). Of the tests included, 12MR showed the strongest correlation with $\dot{V}O_2$max ($r = 0.78$, 0.72-0.83); however, in this meta-analysis, the magnitude of the error associated with 12MR differed greatly. These variations may be reconciled by Bland-Altman analysis of the 12MR prediction showing a trend towards underestimation and overestimation in individuals with lower or higher $\dot{V}O_2$max values, respectively (Penry et al., 2011).

Given that when introducing the 12MR, Cooper (1968) did not report any physiologic parameters of aerobic or anaerobic fitness besides $\dot{V}O_2$max, the prediction equation assumes that other variables have a negligible impact on performance. This assumption ignores our present understanding of fatigue and exercise tolerance during exercise in the severe intensity domain, and could explain much of the observed error. Factors influencing performance independent of $\dot{V}O_2$max would lead an individual to under or overestimate $\dot{V}O_2$max as a function of their difference from the mean levels in Cooper's original data. Of particular interest with regards to high intensity exercise tolerance are the critical speed (CS) and severe domain distance capacity (W') concepts (Jones et al., 2010).

Critical Speed and Severe Domain Distance Capacity

Initially introduced for intermittent isometric contractions, the power–time to exhaustion (P–TE) relationship is linear and inverse during exercise in the severe intensity domain (Monod & Scherrer, 1965). In applying these observations to whole body dynamic exercise, this relationship has been shown to exist and investigated extensively in the cycling literature (Jones et al., 2010; Moritani et al., 1981). The early advent of the P–TE relationship in cycling is largely attributable to the capability of cycling power meters to directly monitor workload. With quantifying power output only feasible during certain endurance exercise modalities however, the same principles have also been applied to activities like running and swimming using speed measures as a proxy for power data (Hughson et al., 1984; Wakayoshi et al., 1992). Given the applicability of the P–TE relationship to modalities utilizing differing metrics and terminology, the remainder of this section will use critical intensity (CI) to describe generalizable concepts, and CS/CP in citing specific examples.

Based upon the linear and inverse relationship described, for a given intensity (I), time to exhaustion (TE) can be represented by the following equation:

$$I = (W' / TE) + CI$$

As written, W' represents the work that can be performed at intensities greater than CI, while CI is given by the asymptote of the I–TE curve (Hughson et al., 1984; Jones et al., 2010). From a purely mathematical standpoint, CI thus represents an intensity that can be maintained for an infinite amount of time without the development of fatigue. The possibility of a speed or workload that can be maintained indefinitely however violates basic physiologic principle, and thus TE at CI may be relatively short in practice. In examining the physiologic profile of running at CS determined from various predictive models, Bull et al. (2008) found that many runners reached volitional exhaustion in less than an hour. Similarly in elite cyclists, McClave et al. (2011) found that CP did not represent a sustainable workload, with an average time to exhaustion to be only 14.79 ± 8.38 minutes. As such, while CI may be defined as the highest intensity at which a steady state $\dot{V}O_2$ and blood lactate concentration can be achieved (Poole et al., 1988), fatigue cannot be solely attributed to work done above CI. Rather, CI may represent a critical neuromuscular fatigue threshold above which exhaustion is predominantly the result of peripheral mechanisms of fatigue (Burnley et al., 2012; Poole et al., 2016).

Mechanistic Basis: With CI and W' determined using performance outcomes as opposed to the measurement of some specific physiologic variable, there may not be a single underlying mechanism that they can be attributed to (Jones et al., 2010). Early work found constant workload cycling performed at 5% of maximal aerobic power below CP to elicit a steady state response in $\dot{V}O_2$ and blood lactate concentration ([BLC]). Conversely, workloads 5% above CP led to a progressive increase in [BLC] and $\dot{V}O_2$, suggesting that CP represents the highest workload at which physiologic steady state can be achieved (Poole et al., 1988). As such, much work has sought to address the cause of these increases. Rossiter et al. (2002) used whole body magnetic resonance spectroscopy to compare the response of muscle phosphocreatine ([PCr]) dynamics to the $\dot{V}O_2$ response seen with high intensity exercise. Depletion of muscle [PCr] was found to be closely related to increases in $\dot{V}O_2$ during high intensity exercise. With these increases in $\dot{V}O_2$ related to [PCr], and with them ultimately being truncated at $\dot{V}O_2$max, TE and W' during severe intensity exercise may be described by metabolic control processes (Burnley & Jones, 2007; Jones et al., 2010). Further evidence suggests that the magnitude of W' may also be related to intramuscular glycogen concentrations (Miura et al., 2000).

Most recently, Vanhatalo et al. (2016) expanded upon the protocol used by Poole et al. (1988) to produce a more complete profile of metabolic responses above and below CP. Constant load cycling trials were performed at 5% of maximal aerobic power both above (CP+5%) and below (CP-5%) CP. An additional trial was also performed at the same workload as CP-5%, but equal in duration to CP+5% (~12 min; CP+5%$_{isotime}$). End-exercise levels of [PCr], [Cr], [La$^-$], and pH for CP+5% differed from both CP-5% and CP+5%$_{isotime}$. CP-5% and CP+5%$_{isotime}$ however, did not differ in any of these variables, suggesting a steady state response below, but not above CP.

Vanhatalo et a. (2016) also studied biopsies taken from the vastus lateralis muscle of a subset of subjects. This examination found a positive correlation between CP and the proportion of type I muscle fibers, suggesting reliance on predominately oxidative pathways. No distinct relationship however, was observed between muscle fiber type and the magnitude of W', suggesting a contribution from both oxidative and non-oxidative pathways.

Determination: Traditionally in determining CS and W', an individual must complete 6 constant speed trials to exhaustion (Hughson et al, 1984). Speeds for these trials should aim to elicit exhaustion between 1-10 minutes, and have been determined in different ways across studies. In early work, these were standard across subjects based on expectation from previous performances (Hughson et al, 1984). More recently, these speeds have been set at various percentages of estimated $\dot{V}O_2$max speed or previously determined maximal aerobic speed (MAS; Bosquet et al, 2006; Bull et al, 2008; Smith & Jones, 2001). The inverse of time to exhaustion for these trials is then plotted with respect to speed, and linear regression is used to determine the line of best fit (Hughson et al, 1984). The slope of this line represents W', whereas the y-intercept represents CS (Figures 1 & 2). While this method is standard across much of the literature, Morton (1996) proposed a 3-parameter model for determining CP and W' that incorporates MAS into its prediction as follows:

$$TE = [W'/(S - CS) - W'/(MAS - CS)]$$

While not as widely used, there is some evidence that the 3-parameter model may predict a more sustainable intensity for CS (Bull et al, 2008). We have chosen not to use this model due to the necessity of an additional test for the determination of MAS

It should be noted that in the cycling literature, a 3-minute all-out test has been introduced that is able to accurately predict CP and W' (Vanhatalo et al, 2008). A similar test has been applied to running, and though it provides a good prediction in most individuals, Bland-Altman analysis reveals an uneven bias, with less aerobically fit individuals tending to score higher on the 3-minute run than on the exhaustive treadmill trials (Maryn et al., *in preparation for publication*)

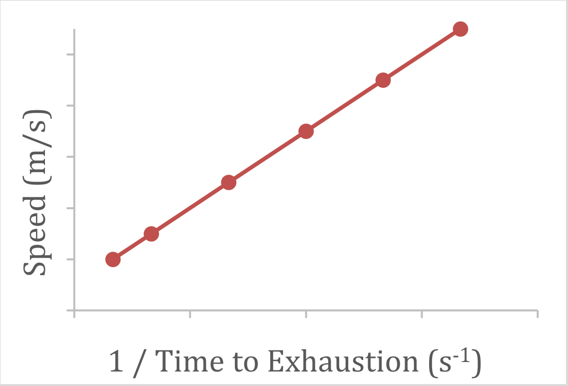

Figure 1: The inverse of time to exhaustion vs speed. Severe domain distance capacity (W') is represented by the slope of the line, and critical speed (CS) is given by the y-intercept

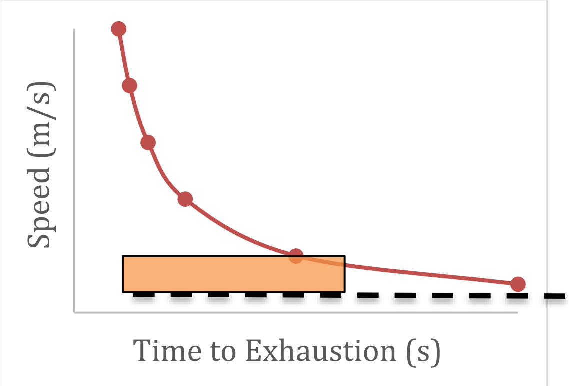

Figure 2: Time to exhaustion vs speed. Critical speed (CS) is represented by the horizontal asymptote, and severe domain distance capacity (W') is represented by the area of the shaded rectangle at any given time.

<u>Performance Implications</u>: Given their relevance to the power-TE relationship, CI and W' have been investigated with respect to various performance measures. Kolbe et al. (1995) examined the relationship between CS and running times for distances ranging from 1-km to 21.1km, with moderate correlation observed (r = -0.75 to -0.85). While these values may lack that sensitivity to accurately predict run times, across distances they were at least as strong as the correlation between run time and $\dot{V}O_2$max (r = -0.75 to -0.81). In a separate study, where 800-m run time predicted by the CS curve was compared to actual 800-m run performance, similarly strong correlations were found (r = 0.83 to 0.94; Bosquet et al., 2006). The range of correlation values in this case was due to various CS values being determined using different models. Following this work up, when W' was compared to 800-m run speed, no correlation between the two was found (r = -0.07 to 0.23) regardless of the model used (Bosquet et al, 2007). These findings may potentially be reconciled by evidence suggesting that training techniques focused on increasing CS, may lead to slight reductions in W' (Jenkins & Quigley, 1992; Vanhatalo et al, 2008). These observations, however, were not statistically significant, and may require further investigation. Had interaction occurred between CS and W' though, in tasks with a strong reliance on oxidative pathways, a weak correlation between W' and performance would be expected. Nevertheless, Pettitt et al. (2012) found W' to be strongly correlated with race speeds above CS in for 800-, 1600-, and 5000-m events in collegiate distance runners.

With the bulk of these data supporting CS as an important predictor of performance, Jones et al (2010) suggest that for an individual to achieve optimal endurance performance, the entirety of the task must be performed at or above CS. In this case, the individual running would be expected to run at CS, fully deplete W' at some point, and return to CS for the remainder of the run post-depletion. With the CS-TE model based purely on a controlled mathematical approach to the scenario however, there is evidence to suggest that it may not be a realistic strategy. While in theory CS represents a fatigueless intensity, several studies have produced results conflicting with this assumption. In testing elite cyclists, McClave et al (2011) found CP to be sustainable for only 14.79 ± 8.38 minutes. Similarly, upon examining moderately trained runners, Bull et al (2008) found CS predictions from various models to be unsustainable across subjects. Only half of their subjects in this case were able to complete a 60-min constant speed trial at the lowest predicted CS value. These findings may in part be explained by recent work that found CP to consistently overestimate maximal lactate steady state (Mattioni Maturana et al, 2016). Conversely, Smith and Jones (2001) found no difference between CS and speed at maximal lactate steady state. While these findings may conflict, they do not necessarily invalidate CI as a predictor of performance. Rather, they simply suggest that more refined modeling techniques should be considered in future work.

Given the clear relationship between these exercise tolerace parameters and endurance performance, it is highly likely that they play a role in the distance an individual can run during the 12MR. It is presently unknown however, the extent of the effect that CS and W' will have. Moreover, it is unknown whether or not these parameters have significant bearing on the $\dot{V}O_2$max-12MR performance relationship. While the 12MR has traditionally been used as a measure of $\dot{V}O_2$max, knowing the extent to which $\dot{V}O_2$max is dictating performance in this test will help further understanding of endurance performance, and will help direct appropriate assessment of endurance athletes.

Limitations

Due to the demanding nature of the study design, a high attrition rate is anticipated. The number of participants was chosen based upon a 20-30% attrition rate and a power calculation to achieve a power level of 0.95 with and alpha level of 0.05. Based on previous work and our present hypotheses, our power calculation expects CS to account for 60-70% percent of the variance in 12MR performance, with $\dot{V}O_2$max and W' having a relatively small contribution. Environmental factors may affect performance during outdoor testing sessions, and as such, criteria have been set that would warrant rescheduling testing sessions. Study participation may not be kept entirely confidential due to the need to perform outdoor testing. This, along with the rigor of the tests being conducted may lead to a self-selection bias among participants. Testing being done in small groups for the 12MR and volitional exhaustion treadmill runs may also contribute to this, however, we anticipate that having others present will provide additional motivation for participants. The age range selected for this study includes primarily young adults. These individuals were selected for safety reasons and so as to minimize cardiovascular disease risk

Summary

The Cooper 12-minute run is a commonly used field test for predicting $\dot{V}O_2$max. While this test is a moderately strong predictor of $\dot{V}O_2$max, it produces inconsistent results across aerobic fitness levels. This may be attributable to the fact that it does not factor other physiological predictors of endurance performance into its estimation. Two prime candidates that would likely impact the distance an individual can run during the 12-minute test are critical speed and severe domain distance capacity. While these are predictors of endurance performance, the extent of their effect on this particular test, along with their interactions with $\dot{V}O_2$max, have not been investigated. This study will examine the relationships between critical speed, severe domain distance capacity, $\dot{V}O_2$max, and 12-minute run performance. In doing so, the data obtained in the study will further our field's understanding of endurance performance potential, and help coaches, athletes, and other researchers more effective determine appropriate field assessments.

9. Subject Population and Recruitment

This study will target active males and females between the ages of 18-35y, who currently engage in running exercise 3 or more times per week for at least 30 minutes per session. Our goal is to recruit 30 active participants. To meet this goal, we may have to screen up to 50 participants to reach 30 eligible who complete the study based on a 30% attrition rate. A maximum of 25 males and 25 females will be screened so as to recruit an equal distribution of genders. Gender will be defined as a participant's biological sex, and will be identified in initial conversations with the participants. The risk level of the target population is low. Women of childbearing age who are not medically sterile will be screened via urine pregnancy test and, if pregnant, will be excluded from the study. These results will not be disclosed to the participant. Rather, when all screening forms have been completed, they will simply be told whether they are eligible to participate or not.

Participants will be recruited through advertisement via flyers, word-of-mouth, KIN class announcements, and emails or social media announcements to collegiate teams, clubs and local athletic clubs within the Willamette Valley and around Oregon, including Bend, Eugene, Salem, Corvallis, Monmouth and McMinnville (see Appendix A: Recruitment Emails and Appendix B: Recruitment Flyer). The investigators will conduct in-class recruitment. The study-related announcements (such as study title and investigator contact information) or recruitment materials (such as fliers) will be provided to students in KIN classrooms where the investigator is not also the class instructor. Recruitment methods will permit students to self-identify outside of the classroom so as to maintain confidentiality and minimize the potential for peer pressure. These areas of Oregon are very popular with runners. The cities of Corvallis, Eugene, and Bend have a relatively high population of high performance endurance athletes, which will allow us to include a wider range of fitness levels in our investigation. Recruiting will take place continuously until all positions have been filled. To prevent an uneven distribution of genders, in the event that male participants are recruited more rapidly than females or vice versa, caps may be set when the necessary number of participants per gender has been reached. Prospective participants will be given the contact information of the PI and student investigator for scheduling. Potential participants will be scheduled for Visit 1.

This study is limited to active participants because the research questions specifically address a field test that is used amongst active individuals. Furthermore, a high attrition rate would be expected amongst sedentary individuals given the nature of the test procedures. Although youth (<18y) participate in endurance events, a separate, age-specific study would be required, which is beyond the scope of this research. Research using children would need to address the confounding effect of growth and development on outcome variables. Participants over 35 years of age will not be included in the study to eliminate menstrual irregularities due to perimenopause and aging, as well as additional risk factors for cardiac disease in males. Some minority groups or subgroups will be poorly represented because the geographical location (Willamette Valley and Central Oregon) of the study has only limited numbers of these minority groups who would be eligible for the study. Non-English speaking participants will be excluded from this project because the research team only speaks English and materials are provided only in English.

Subjects will be invited to participate if they meet the following Inclusion criteria:

- Between the age of 18-35y
- Run 3 or more times for at least 30 minutes in a typical week.

Subjects will be excluded from the study if they meet any of the following exclusion criteria:

- Have any risk factors from section 1 or have more than 1 of the cardiovascular risk factors listed in section 2 of the IRB-supplied health history questionnaire (See Appendix C: Health History Questionnaire).

- Are pregnant, lactating, or are planning to become pregnant during the course of her participation in the study
- Are planning to change training status during the scheduled testing period
- Are injured or have not fully recovered from a recent injury
- Are unable to attempt a maximal test

Information from Appendix C: Health History Questionnaire will be used to screen for exclusion criteria 1-2 listed above. Information from Appendix D: Supplemental Health History Questionnaire will be used to screen for exclusion criteria 2-5. In the event that a participant does not qualify for the study, the specific criteria disqualifying them will not be disclosed. Instead, they will simply be told that they have been screened as ineligible.

10. Consent Process

Upon the first visit, prior to engaging in any study activities, a verbal description of the study will be given by one of the researchers. At this time, we will discuss the criteria for participation and let them know that additional information they provide on the questionnaires may make them ineligible for study participation. This will allow potential participants to learn more about the study and ask questions before signing the consent form. The participants will be given ample opportunity to review the consent document and ask the researchers any questions prior to signing the document. Asking the potential participant the following questions will assess comprehension of the informed consent process:
What questions can I answer for you?
So that I am sure that you understand what the study involves, would you please tell me what you think we are asking you to do?
In your own words, can you tell me what the biggest risk to you might be if you enroll in this study?

After the potential participant has had their questions answered, both the potential participant and researcher will sign the informed consent document. The informed consent process will take place in a private room with only the potential participant and researchers present in order to maintain privacy and confidentiality.

We will not enroll children in this study. We will not enroll non-English speakers (e.g. researchers only speak English and all materials are in English) or adult subjects with diminished capacity to consent. We do not anticipate any significant new findings to affect subjects' willingness to participate in the research study.

11. Eligibility Screening

Participants screening will include health history including cardiovascular medical history, symptoms, other health issues and cardiovascular risk factors. Blood pressure and all other cardiovascular disease risk factors will be reported via self-report. Please see the IRB-supplied Health History Questionnaire and the supplemental health questionnaire (Appendices C and D).

Prior to the first visit to the study site, self-eligibility will be assessed via email to determine if participants meet inclusion criteria (see Appendix A: Recruitment Materials- Email Eligibility Self-Screener). We will use a separate, private, password-protected email address that only the aforementioned researchers have access to in order to self-screen potential participants. Using this private email, we will send the eligibility-screening questionnaire to potential participants who will selfdetermine if they meet the inclusion criteria (see Appendix A: Recruitment Materials- Email Eligibility Self-Screener). If a potential participant self-identifies that they are eligible, they will notify us by phone or email and we will set up a meeting with them for further screening. Non-English speaking persons will be excluded from this project because study team members only speak English and all study materials are in English.

12. Methods and Procedures

Prior to testing, if the participant indicates he/she has greater than mild pain before initiating a testing bout, or gives indication of other variables that may interfere with optimal testing experience, that session will be rescheduled before the end of the six-week test period. If the participant indicates that they are not comfortable performing exercise testing in front of a certain individual, they will be given the opportunity to reschedule that testing session before the end of the six-week test period. They will not be penalized in any way for choosing to reschedule.

Instruments: A ParvoMedics TrueMax 2400 metabolic cart will be used to assess $\dot{V}O_2$ (ParvoMedics, Sandy, UT). A Polar heart rate (HR) monitor (Polar, Lake Success, NY) will be used to measure HR. Tests for $\dot{V}O_2$max and CS will be conducted on a TrackMaster treadmill (Full Vision, Newton, KS). An InBody 770 bioelectrical impedance analysis system (InBody, Cerritos, CA) will be used to assess body composition.

Overview: Each individual will visit the lab on three to four occasions and an all weather track in the greater Corvallis area once. Participants will complete four testing sessions in random order: one treadmill graded exercise test, one 12-minute run test, and two series of volitional exhaustion treadmill runs. The first session will include preliminary screening and if desired can be combined with the second session which will include a body composition test and the first randomized test. In the event that a participant's first test is conducted at the track, the body composition test will be performed at the start of their second visit. The third, fourth, and fifth sessions will include the other tests, again in randomized fashion. Participants will be encouraged to give a maximal effort during each test. Participant total time commitment is approximately 4-5 hours.

Testing conditions in the laboratory will be maintained at approximately 22 degrees Fahrenheit and approximately 30% humidity. Given that environmental conditions may be unpredictable for outside testing, conditions that would warrant rescheduling testing will be considered any of the following: wind chill below 7 degrees Celsius or heat index exceeding 24 degrees Celsius, and wind speeds above 8 kilometers per hour. Temperature and barometric conditions will be measured immediately before initiating a testing session.

Visit 1 (0.5-0.75 h): Informed Consent, Questionnaires

After the participant has reviewed the email self-screening criteria (Appendix A), subjects will be provided the informed consent document and will be given the opportunity to ask any questions they have prior to signing the document. Before signing the informed consent, participants will be informed that information provided in the questionnaires might further eliminate them from the study. No screening data will be collected until after the informed consent has been signed.

Once the participant has had the chance to ask questions and informed consent has been given, the participants will complete a confidential set of questionnaires: Health History Questionnaire, Supplemental Health History Questionnaire. Copies of these questionnaires are in Appendices C and D. Women of childbearing age who are not medically sterile will then be screened via urine pregnancy test and, if pregnant, will be excluded from the study. If a participant indicates that they intend to become pregnant over the course of their participation in the study, they will also be excluded. The researchers (Penry or Seipel) will confidentially review questionnaires with the participant before they leave to assure completeness of the documents and discuss any issues that may arise. Any issues related to eligibility will be discussed within the research group and reviewed with the participant, if necessary.

Dates will be scheduled for visits 2-5.

Participants will be informed of the general consideration and instructions prior to the first exercise test:

General considerations. Participants will be asked to (1) maintain their current activity level, (2) refrain from any structured exercise for the 24-hour period prior to a testing session, (3) refrain from eating for at least 2 hours prior to the test , and (4) to consume the same meal prior to each test. The above considerations will be verified by interview and a self-report. Participants must wait at least 48-hours between testing bouts. Participants must complete all four testing sessions within a six-week period but will be encouraged to complete testing within three to four weeks to minimize any training effect that may occur. If they are not able to complete testing within a six-week period, they will be withdrawn from the study. Upon arrival for visits 2-5, participants will be verbally asked if they have met the general considerations. If they have not, the visit will be rescheduled. Female participants who are not medically sterile will be asked to report any suspected pregnancy to the researchers. In the event of this, prior to their continued participation in the study the participant will be required to produce written documentation from a physician indicating that they are not pregnant.

Visit 2 (1-1.5 h): Body Composition Test, Lab Running Exercise Test 1

Participants will report to the OSU Human Performance Laboratory (Women's Building, Room 19) after a 2-h fast and greater than 24-h since their last exercise session. Participants will be verbally asked if they have met the general considerations. Height and weight will be measured using a standard stadiometer and scale, respectively. Body composition will be measured using the InBody770 (InBody, Cerritos, CA USA). After completion of body composition testing, the first running exercise test will be performed. If desired and indicated via e-mail screening, the participant may choose to combine visits one and two.

Visit 3 (0.75-1.25 h): Lab Running Exercise Test 2

Participants will report to the OSU Human Performance Laboratory (Women's Building, Room 19) in after a 2-h fast and greater than 24-h since their last exercise session. Participants will be verbally asked if they have met the general considerations. Height and weight will be measured using a standard stadiometer and scale, respectively. The second running exercise test will be performed.

Visit 4 (0.75-1.25 h): Lab Running Exercise Test 3

Participants will report to the OSU Human Performance Laboratory (Women's Building, Room 19) in after a 2-h fast and greater than 24-h since their last exercise session. Participants will be verbally asked if they have met the general considerations. Height and weight will be measured using a standard stadiometer and scale, respectively. The last running exercise test will be performed.

Visit 5 (0.75 h): Cooper 12-Minute Run

Participants will report to an all-weather 400-meter track in the greater Corvallis area after a 2-h fast and greater than 24-h since their last exercise session. Participants will be verbally asked if they have met the general considerations and will be provided with pre-test instructions. The 12-minute run test will be performed.

Detailed Methods and Laboratory Procedures

Prior to the initiation of any testing, the Trackmaster treadmill will be calibrated based upon manufacturers instructions.

Maximal Graded Exercise Test: This testing will be completed in the Oregon State University Human Performance Laboratory, and will be conducted using a ParvoMedics TrueMax 2400 metabolic cart and a Polar HR monitor while the participant runs on a Trackmaster treadmill. Prior to testing, calibrations will be performed for gas exchange using a known O_2–CO_2 mixture, and for flow rate using a known-volume syringe.

Prior to this test, participants will be fitted with a nose clip and mask equipped with two one-way valves connected to the metabolic cart, to allow for the collection of expired gases throughout the test. Participants will then perform a 3-minute warm-up at a 0% gradient. Starting speed will be estimated based upon running experience reported in the supplemental health history questionnaire (Appendix D) and self-described approximation of current running fitness level. This speed will range from 8.0 to 11.0 km/hr with the goal of having the test last between 12 and 15 minutes. Following this warm-up, grade will be increased to 3%, signifying the start of the test. Stages will be set at 1 minute in duration, with speed or incline increased at the end of each stage. Rating of perceived exertion (RPE) will be collected halfway through each stage (Borg, 1982). Speed will be adjusted first and will be increased by 0.8 km/hr at the end of every minute until the participant reaches a RPE of 13. From this point, speed will be kept constant and incline will be increased by 1% grade at the end of each stage until the participant indicates that he/she is unable to continue. Immediately following the final stage of the test, participants will be encouraged to walk at an easy pace to ensure appropriate cool down. Participants will be allowed to cool down at a self-selected pace

During the cool down phase the researchers will assess the participant's $\dot{V}O_2$ data. For the test to be considered maximal, participants will need to exhibit an increase of less than 2.1 mL/kg/min in minute oxygen consumption across the final two stages. If this plateau is achieved, $\dot{V}O_2max$ will be taken as the maximum value recorded for a completed stage during the test. In the event that a plateau is not achieved, a verification stage will be performed. This will only be done if the participant does not reach a plateau in ventilatory oxygen uptake at the end of the maximal test. Following a 10-minute cool-down period, speed and incline will gradually be increased over the next two minutes to the intensity reached during the final stage of the maximal test. After one minute at this intensity, incline will be increased by 1% grade and the participant will be encouraged to maintain this intensity for two minutes. If they are able to maintain at least one minute at this intensity and the final minute-averaged $\dot{V}O_2$ value obtained is within 2.1 mL/kg/min of the final value obtained during the initial test, a plateau will have been achieved. If the participant completes the full 2 minutes at the increased intensity and a plateau in oxygen consumption is not observed, another 10-minute cool-down will be performed and the verification stage protocol will be repeated, but with an increase of 2% grade instead. If a plataeu is achieved, the maximum $\dot{V}O_2$ value recorded during these verification trials will be considered a participant's $\dot{V}O_2$max. In the event that the participant is unable to sustain one minute at the intensity of the verification stage, or if they fail to reach a plateau after the second verification stage, the subject's participation in the study will end.

Results of the VO_{2max} test will be provided to the participants upon completion or withdrawl from the study.

<u>Volitional Exhaustion Treadmill Runs</u>: Prior to testing, participant will be asked to sit for 5 minutes to determine a baseline HR using a Polar HR monitor. To determine CS and W', the procedures described in Hughson et al. (1984) will be employed. Over two testing days, participants will perform six runs to volitional fatigue at different speeds on the treadmill, with speeds for these trials intended to elicit exhaustion between one and 10 minutes. Speeds will be approximated based upon running experience reported in the supplemental health history questionnaire (Appendix D), self-described approximation of current running fitness level, and previous test performance. Prior to testing, subjects will be allowed a 10-minute period at a self-selected warm-up speed. Subjects will be instructed not to exceed an RPE of 16 during this warm-up to prevent premature fatigue or a priming effect on the $\dot{V}O_2$ slow component (Bailey et al., 2009). Trial order will be randomized and time to exhaustion recorded for each trial. Participants will rest between trials and will be considered adequately recovered when their heart rate reaches a value within 20 beats per minute of the pre-exercise baseline heart rate. Following the second trial, this recovery procedure will be repeated, and following the third trial, participants will be encouraged to cool down at a self-selected pace. To determine CS, the speed of each individual trial will be plotted against the inverse of time to exhaustion for the respective trial. The y-intercept of the line of best fit for each plot will be taken as that participant's CS, and will be determined using linear regression. The slope of this line will represent the value of W'.

Results of the volitional exhaustion treadmill runs will be provided to the participants upon completion or withdrawl from the study.

<u>Cooper 12-Minute Run</u>: The 12MR will be performed on a standard 400-meter outdoor track, as described by Cooper (1968). Prior to testing, participants may perform a 10-minute warm-up at a self-selected speed, but will be instructed not to exceed an RPE of 16 during this warm-up to prevent premature fatigue or a priming effect on the $\dot{V}O_2$ slow component (Bailey et al., 2009). Participants will be instructed to complete as many laps as possible within a 12-minute time period. It will be emphasized that the test is intended to be completed at a maximal effort, but that participants should try to adopt a pacing strategy that will not cause premature fatigue or inability to complete the test. This test will be performed in small groups of 2-4 participants of similar fitness levels to optimize motivation. Participants will be instructed not to draft. Time will be recorded for each participant at 400-meter intervals, with any substantial changes in pacing noted. The test administrator will record the number of laps completed and will indicate the elapsed time at 3, 6, and 9 minutes into the test via a whistle signal. Participants will otherwise be blinded to time and will not be permitted to wear a watch. Between 10 and 11 minutes into the test, the researchers will approximate the participant's end point(s) based upon pacing, and head toward these general areas so as to mark participant end points as quickly as possible. When the 12-minute period is complete, participants will be instructed to stop immediately via a final whistle signal. Once the researchers have marked the final positions, the participants will be

encouragaed to perform a cool down at a self-selected pace. The distance completed for the final lap will be determined using a measuring wheel.

InBody770: The InBody770 will be turned on prior to participant arrival. If participants are wearing heavyweight clothing, they will dress down to lightweight clothing such nylon shorts and a t-shirt. Participants will be asked to stand for 10 minutes prior to testing. Height and weight will be measured using a standard stadiometer and the InBody scale, respectively. Participants will be instructed to stand on the InBody electrode platform and grasp the electrode handles. They will then be asked to stand with their arms in straight, with approximately 30^0 of shoulder abduction. This position will be held for one to two minutes, while body composition is assessed via bioelectrical impedance.

Statistics

A stepwise multiple regression analysis will be performed with CS, W', and $\dot{V}O_2$max as independent variables and 12MR distance set as the dependent variable ($\alpha = 0.05$). From the stepwise multiple regression analysis, the first order CS-$\dot{V}O_2$max, CS-W', and $\dot{V}O_2$max-W' relationships will also be assess to determine any interaction effect.

13. Compensation

No monetary compensation will be given to those individuals who participate in this study.

14. Costs

Participants will not be charged for any tests that are performed for the purposes of this study. Participants and/or their insurance provider will be responsible for all other medical care expenses. Participants will be responsible for travel costs to the study site.

15. Medical Devices

No medical devices for invasive data collection will be used in this study. We will use an InBody770 for assessment of body composition, and a ParvoMedics TrueMax 2400 metabolic cart will be used to assess gas exchange data.

16. Anonymity or Confidentiality

Participants will be described as "Participant" plus participant number (i.e. "Participant 1", "Participant 2", "Participant 3", etc.). All participants' files will be identified by "Participant" plus number or "P" plus participant number. Their names or any information that will readily identify them will not be used in any published data. Should any responses to demographic questions potentially lead to an individual participant being identifiable, we will not report this information in any published data. An electronic document containing a link between identifiers and coded data will be retained with the PI until the study is complete and articles published (5y). Signed consent forms will be stored separately from coded data. All data will be securely locked in Women's Building 19.

Data will be kept in securely locked file cabinets. Any information collected via written, paper questionnaires will be store in a securely locked cabinet after it has been saved electronically using participant code numbers (no names). Paper questionnaires will only have participant code numbers on the documents. All individual identifiers will be removed. Electronic data will be kept on a password-protected computer with a fully patched operating system and applications, and current antivirus software and virus definitions through Avast Antivirus. When this computer is not in use by members of the research team, it will be kept securely locked up. At the end of each day that data are collected, electronic documents will be backed up to the OSU Google Drive server and an external hard drive that will be kept in a locked desk for the duration of the study. The only people that will have access to this data and information will be the research team. All data, including written, paper questionnaires and the electronic document containing a link between identifiers and coded data, will be retained for a minimum of five years after study completion. Once manuscripts are published (5y) all paper data will be destroyed. Electronic unidentifiable (no names only participant code numbers) data will be retained with the PI for another 3y.

17. Risks

The risks of $\dot{V}O_2$max and Critical Speed testing are as follows:

- Acute exercise may present a risk of untoward events, including sudden death
- Cardiovascular event (i.e., heart attack or cardiac arrhythmia)
- Overall risk of cardiac events is about 6 events per 10,000 tests
- Serious injury
- Falling
- Physical discomfort
- Fatigue
- Muscle aches, cramps, joint pain
- Muscle strain and/or joint injury
- Delayed muscle soreness
- Abnormal blood pressure/heart rate
- Shortness of breath
- Lightheadedness, fainting
- Dizziness
- Nausea

Every test will be monitored by a member of the research team that has completed the required training to administer and interpret these tests. Tests will be terminated if a study participant exhibits:

- Onset of angina or angina-like symptoms
- Shortness of breath, wheezing, leg cramps or claudication
- Signs of poor perfusion: light-headedness, confusion, ataxia, pallor, cyanosis, nausea or cold/clammy skin
- Failure of heart rate to increase with increased exercise intensity
- Noticeable change in heart rhythm
- Physical or verbal manifestations of severe fatigue

Additionally, the test will be terminated if:

- Participant requests to stop
- The testing equipment fails

There are no anticipated risks from the body composition assessment using bioelectrical impedance.

ACSM recommendations for test termination based upon blood pressure measures are excluded, as blood pressure will not be monitored during testing. All other ACSM recommendations will be taken into account.

Emergency procedures include an automatic external defibrillator (AED) located in the same room as the testing equipment and an emergency action plan on file with the department. The PI and all members of the research team are trained in the use of the AED and possess current BLS/AED certifications. The equipment is regularly inspected to ensure its function. The study team will be familiarized with the emergency procedures should an event arise, with the Emergency Action Plan posted at the lab testing site and copies given to each member of the team during outdoor testing sessions.

All gas analysis equipment will be sterilized using a wide-spectrum antimicrobial disinfectant (Cidex). Equipment that cannot be sterilized using this disinfectant will be cleaned using detergent and water.

Laboratory surfaces will be cleaned using disinfectant wipes.

18. Benefits

Participants will receive a measure of both maximal oxygen consuption and body composition as a result of participating in this study. In addition, participants will receive measures of critical speed, anaerobic capacity (severe domin distance capacity), and gas exchange threshold that may be used for prescription of training intensities for maximizing adaptations to endurance training.

For society this study will allow for a better understanding of factors influencing performance on a common field test for assessing cardiorespiratory fitness. Moreover, understanding interaction among these predictors of endurance performance, could help dictate what tests and measures are used to assess endurance performance potential and cardiorespiratory fitness in the future. Field testing for these measures proves beneficial to many individuals who don’t have access to lab facilities. As such, by examining the utility of our current assessment tools, we can direct improvements in testing protocols, thus allowing coaches and practitioners to improve the services that they are able to provide with fewer resources.

19. Assessment of Risk:Benefit ratio

Participants will experience short-term fatigue when completing the volitional exhaustion treadmill runs, the 12-minute run, and the maximal graded cycling exercise test. The fatigue is similar to that felt after a challenging interval workout or a five-kilometer running race. There is a very remote chance that individuals may suffer a heart attack during these maximal efforts, although this will be a very low risk for the study participants, since the pre-screening will have determined them to be physically active and apparently healthy.

The use of field testing to predict markers of cardiorespiratory fitness is invaluable when laboratory equipment is unavailable, as is the case for most individuals. By seeking to better understand the role of various physiological measures in performance on a commonly used assessment, our results will be able to help direct which tests and measures are used in the future. The continued development of field tests to determine useful assessment and training parameters is important. It allows for more frequent and less expensive testing methods, but more valid and effective testing methods. By critically evaluating these tests, individuals without extensive resources are directed towards appropriate data that can provide them a means of tracking progress and directing future training, that would be otherwise inaccessible.

References

Bailey, S. J., Vanhatalo, A., Wilkerson, D. P., Dimenna, F. J., & Jones, A. M. (2009). Optimizing the “priming” effect: influence of prior exercise intensity and recovery duration on O2 uptake kinetics and severe-intensity exercise tolerance. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *107*(6), 1743–1756. https://doi.org/10.1152/japplphysiol.00810.2009

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Bosquet, L., Duchene, A., Lecot, F., Dupont, G., & Leger, L. (2006). Vmax estimate from three-parameter critical velocity models: validity and impact on 800 m running performance prediction. *European Journal of Applied Physiology*, *97*(1), 34–42. http://doi.org/10.1007/s00421-006-0143-7

Bosquet, L., Delhors, P. R., Duchene, A., Dupont, G., & Leger, L. (2007). Anaerobic running capacity determined from a 3-parameter systems model: relationship with other anaerobic indices and with running performance in the 800 m-run. *International Journal of Sports Medicine*, *28*(6), 495–500. http://doi.org/10.1055/s-2006-924516

Bull, A. J., Housh, T. J., Johnson, G. O., & Rana, S. R. (2008). Physiological responses at five estimates of critical velocity. *European Journal of Applied Physiology*, *102*(6), 711–720. http://doi.org/10.1007/s00421-007-0649-7

Burnley, M., Vanhatalo, A., & Jones, A. M. (2012). Distinct profiles of neuromuscular fatigue during muscle contractions below and above the critical torque in humans. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *113*(2), 215–223. https://doi.org/10.1152/japplphysiol.00022.2012

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

Cooper, K. H. (1968). A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. *JAMA*, *203*(3), 201–204.

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A high velocity treadmill running test to assess endurance running potential. *International Journal of Sports Medicine*, *5*(1), 23–25. http://doi.org/10.1055/s-2008-1025875

Jenkins, D. G., & Quigley, B. M. (1992). Endurance training enhances critical power. *Medicine and Science in Sports and Exercise*, *24*(11), 1283–1289.

Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports Medicine (Auckland, N.Z.)*, *29*(6), 373–386.

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of $\dot{V}O_2$max and exercise tolerance. *Medicine and Science in Sports and Exercise*, *42*(10), 1876–1890. http://doi.org/10.1249/MSS.0b013e3181d9cf7f

Kolbe, T., Dennis, S. C., Selley, E., Noakes, T. D., & Lambert, M. I. (1995). The relationship between critical power and running performance. *Journal of Sports Sciences*, *13*(3), 265–269. https://doi.org/10.1080/02640419508732236

Mattioni Maturana, F., Keir, D. A., McLay, K. M., & Murias, J. M. (2016). Can measures of critical power precisely estimate the maximal metabolic steady state? Applied Physiology, Nutrition, and Metabolism. http://doi.org/10.1139/apnm-2016-0248

Mayorga-Vega, D., Bocanegra-Parrilla, R., Ornelas, M., & Viciana, J. (2016). Criterion-Related Validity of the Distance- and Time-Based Walk/Run Field Tests for Estimating Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis. *PloS One*, *11*(3), e0151671. http://doi.org/10.1371/journal.pone.0151671

McClave, S. A., LeBlanc, M., & Hawkins, S. A. (2011). Sustainability of Critical Power Determined by a 3-Minute All-Out Test in Elite Cyclists: *Journal of Strength and Conditioning Research*, *25*(11), 3093–3098. https://doi.org/10.1519/JSC.0b013e318212dafc

McLaughlin, J. E., Howley, E. T., Bassett, D. R., Thompson, D. L., & Fitzhugh, E. C. (2010). Test of the classic model for predicting endurance running performance. *Medicine and Science in Sports and Exercise*, *42*(5), 991–997. http://doi.org/10.1249/MSS.0b013e3181c0669d

Monod, H., & Scherrer, J. (1965). The Work Capacity of a Synergic Muscular Group. *Ergonomics*, *8*(3), 329–338. http://doi.org/10.1080/00140136508930810

Moritani, T., Nagata, A., Devries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24(5), 339–350. http://doi.org/10.1080/00140138108924856

Morton, R. H. (1996). A 3-parameter critical power model. *Ergonomics*, *39*(4), 611–619. https://doi.org/10.1080/00140139608964484

Penry, J. T., Wilcox, A. R., & Yun, J. (2011). Validity and reliability analysis of Cooper's 12-minute run and the multistage shuttle run in healthy adults. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *25*(3), 597–605. http://doi.org/10.1519/JSC.0b013e3181cc2423

Pettitt, R. W., Jamnick, N., & Clark, I. E. (2012). 3-min all-out exercise test for running. *International Journal of Sports Medicine*, *33*(6), 426–431. https://doi.org/10.1055/s-0031-1299749

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. Medicine and Science in Sports and Exercise. http://doi.org/10.1249/MSS.0000000000000939

Poole, D. C., Ward, S. A., Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, *31*(9), 1265–1279. http://doi.org/10.1080/00140138808966766

Rossiter, H. B., Ward, S. A., Kowalchuk, J. M., Howe, F. A., Griffiths, J. R., & Whipp, B. J. (2002). Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on- and off-transients of moderate- and high-intensity exercise in humans. *The Journal of Physiology*, *541*(Pt 3), 991–1002. http://doi.org/10.1113/jphysiol.2001.012910

Shephard, R. J. (2009). Maximal oxygen intake and independence in old age. *British Journal of Sports Medicine*, *43*(5), 342–346. http://doi.org/10.1136/bjsm.2007.044800

Smith, C. G., & Jones, A. M. (2001). The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *European Journal of Applied Physiology*, *85*(1-2), 19–26.

Vanhatalo, A., Black, M. I., DiMenna, F. J., Blackwell, J. R., Schmidt, J. F., Thompson, C., … Jones, A. M. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationships to muscle fibre type. *The Journal of Physiology*. http://doi.org/10.1113/JP271879

Vanhatalo, A., Doust, J. H., & Burnley, M. (2008). A 3-min all-out cycling test is sensitive to a change in critical power. *Medicine and Science in Sports and Exercise*, *40*(9), 1693–1699. http://doi.org/10.1249/MSS.0b013e318177871a

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. *European Journal of Applied Physiology and Occupational Physiology*, *64*(2), 153–157.

APPENDIX B: INFORMED CONSENT

CONSENT FORM

Project Title: **Addressing Error in the Cooper 12-Minute Run**
The Influence of Exercise Tolerance Parameters

Principal Investigator: Jason Penry, Ph.D.
Student Researcher: Aaron Seipel, Morgan Anderson, Stephanie Baxter, Micah White, Arthur Chan
Co-Investigator(s):
Sponsor: none
Version Date: 10/12/17

WHAT IS THE PURPOSE OF THIS FORM?

This consent form gives you the information you will need to help you decide whether to be in the study or not. Please read the form carefully. You may ask any questions about the research, the possible risks and benefits, your rights as a volunteer, and anything else that is not clear. When all of your questions have been answered, you can decide if you want to be in this study or not.

WHY IS THIS RESEARCH STUDY BEING DONE?

The purpose of this research study is to investigate the role of critical speed and severe domain distance capacity in influencing performance during the Cooper 12-minute run test. The 12-minute run is commonly used as a field test for estimating maximal oxygen consumption. This estimation does not factor in other predictors of endurance performance. As such, the assumed relationship may simply be the result of interaction with other physiological variables. The information acquired in this study will improve understanding of maximal oxygen consumption's utility in predicting endurance performance potential. Moreover, it will allow for more informed interpretation of 12-minute run test results by coaches and athletes.

Up to 50 participants may be invited to take part in this study. The investigators intend to publish these findings in a peer-reviewed journal and present these results at a professional conference in the near future. This study will also serve as the masters thesis research for Aaron Seipel, one of the student investigators named above.

WHY AM I BEING INVITED TO TAKE PART IN THIS STUDY?

You are being invited to take part in this study because you are between the age of 18 and 35 years old, currently run at least 3 days per week, and are not currently injured, pregnant, or lactating. Additionally, you believe that you are capable of completing maximal aerobic exercise, and have no more than one cardiovascular disease risk that you are aware of.

WHAT WILL HAPPEN IF I TAKE PART IN THIS RESEARCH STUDY?

During this study, you will participate in one 12-minute run test, six treadmill runs to volitional fatigue, one maximal graded exercise test, and one body composition test. Each test day will be followed by at least 24 hours of rest and you will be asked to complete all tests within a six-week period. Your total time commitment is approximately 4 hours.

You are asked to maintain your current activity level and refrain from structured exercise for the period of 24 hours before each test. In addition, we ask that you refrain from eating for at least 2 hours prior to the test and consume the same meal prior to each test. We will ask you about each of these considerations each time you visit the lab for a testing session. Each testing session will be separated by a minimum of 48 hours.

Descriptions of each test follow below:

Maximal graded exercise test. This is an exercise test that progresses from low to high intensity to measure the maximal rate at which your body can use oxygen during physical activity. This test will be conducted on a treadmill in the Oregon State University Human Performance Laboratory and will require you to run for 12-18 minutes. You will wear a mask to collect the air you breathe out during the test. During this test, speed or gradient will increase every minute until you can no longer continue. Speed will be increased first, and gradient will be increased in the latter stages of the test. In some cases, an additional 5-minute stage will be necessary at your maximal effort. The fatigue experienced following this test will be similar to that felt after completing a five-kilometer running race.

Volitional exhaustion treadmill runs. These tests will be conducted on a treadmill in the Oregon State University Human Performance Laboratory and will be conducted over two visits. You will select your own warm up intensity for 10 minutes. Speeds will be selected to elicit fatigue between one and ten minutes. Upon exhaustion, you will be given the opportunity to rest and recover until your heart rate decreases to within less than 20 beats per minutes above pre-test levels. When you feel adequately recovered and heart rate recovery criteria have been met, the test will be repeated at a different speed. Three trials will be performed per visit to the laboratory with the same recovery protocol used between each trial. After completing the third trial, you may cool down as you wish.

12-minute run. This test will be conducted at an all-weather 400-meter running track in the greater Corvallis area. You will select your own warm up intensity for 10 minutes. Following a warm up, you will be asked to run as far as possible in a 12-minute period. While you will not be permitted to wear a watch, we will provide a whistle signal 3-, 6-, and 9-minutes into the run. A final whistle signal will be given at the 12-minute mark, at which point you must stop immediately. Once an investigator has marked your ending point, you will be permitted to cool down as you wish.

Body composition test. This test will be conducted in the Oregon State University Human Performance Laboratory and involves measuring your body composition by bioelectrical impedance. In order to get accurate results, you cannot eat or exercise for 2 hours before this test and need to be well hydrated. You will stand stationary barefoot on two electrodes, while holding two electrodes at your side. This test should take approximately 15 minutes.

WHAT ARE THE RISKS AND POSSIBLE DISCOMFORTS OF THIS STUDY?

You can expect to experience short-term fatigue when completing the volitional exhaustion treadmill runs and the maximal exercise test. There is also a very remote chance that you may suffer a heart attack during a maximal running effort. For physically active individuals with one or fewer cardiovascular disease risk factors, this is considered a low risk. If further screening classifies you as greater than low risks, you will be ineligible to participate in the study. As such, the risk associated with any exercise testing performed will be low. In addition, every effort will be made to ensure that the areas in which the tests are conducted are free of obstacles that may cause injury.

The possible risks and/or discomforts associated with the exercise testing in the study include:

Acute exercise may present a risk of sudden death
Cardiovascular event (i.e., heart attack or cardiac arrhythmia)
Overall risk of cardiac events is about 6 events per 10,000 tests
Serious injury
Falling
Physical discomfort from the test and equipment
Fatigue
Muscle aches, cramps, joint pain
Muscle strain and/or joint injury
Delayed muscle soreness
Abnormal blood pressure/heart rate
Shortness of breath
Lightheadedness, fainting
Dizziness
Nausea

There are no anticipated risks from the body composition assessment using bioelectrical impedance.

WHAT HAPPENS IF I AM INJURED?

Oregon State University has no program to pay for research-related injuries. If you think that you have been injured as a result of being in this study, please contact the researchers immediately via Dr. Jason Penry, Principal Investigator, at 541-737- 3265 or jay.penry@oregonstate.edu.

WHAT ARE THE BENEFITS OF THIS STUDY?

We do not know if you will benefit from being in this study. However, you will receive information concerning your maximal aerobic capacity, critical speed, and gas exchange threshold heart rate as a result of participating in this study. In addition, you will receive an estimate of your current body composition and basal metabolic rate. Moreover, in the future, other people might benefit from this study, as it will allow coaches, other athletes or researchers to better understand the utility of maximal oxygen consumption in predicting endurance performance potential. This will be particularly useful in identifying the appropriate tests for assessing and tracking improvements in endurance athletes.

WILL I BE PAID FOR BEING IN THIS STUDY?

You will not be paid for being in this research study.

WILL IT COST ME ANYTHING TO BE IN THIS STUDY?

You **will not** be charged for any tests that are being performed for the purposes of this study. You will be responsible for travel costs to the study site.

WHO IS PAYING FOR THIS STUDY?

The Oregon State University Human Performance Laboratory fund is paying for this research.

WHO WILL SEE THE INFORMATION I GIVE?

The information you provide during this research study will be kept confidential to the extent permitted by law. Research records will be stored securely and only researchers will have access to the records. Federal regulatory agencies and the Oregon State University Institutional Review Board (a committee that reviews and approves research studies) may inspect and copy records pertaining to this research. Some of these records could contain information that personally identifies you. To help ensure confidentiality, we will use identification code numbers on data forms instead of your name, and will keep all personal information and study data in a locked filing cabinet. Any digital files that are created will be secured via password protection.

During the 12-minute run and volitional exhaustion treadmill runs, two to four subjects may be tested simultaneously to encourage maximal effort during all these trials. While participation in the study will not be completely confidential amongst subjects due to this, your personal information will not be disclosed to other participants. To minimize the risk of your results being disclosed to other participants during these tests, no results will be given until completion of all tests. In the event that other participants are present during your final test, results will be shared privately at a later time or via email based on your personal preference.

We will make every effort to protect your identity but there is a risk that information, which identifies you, could be accidentally disclosed.

If the results of this project are published, your identity will not be made public.

WHAT OTHER CHOICES DO I HAVE IF I DO NOT TAKE PART IN THIS STUDY?

Participation in this study is voluntary. If you decide to take part in the study, it should be because you really want to volunteer. You will not lose any benefits or rights you would normally have if you choose not to volunteer. If you decide to participate, you are free to withdraw at any time without penalty. You will not be treated differently if you decide to stop taking part in the study. If you choose to withdraw from this project before it ends, the researchers may keep information collected about you and this information may be included in study reports.

WHO DO I CONTACT IF I HAVE QUESTIONS?

If you have any questions about this research project, please email Jason Penry (jay.penry@oregonstate.edu) or Aaron Seipel (seipela@oregonstate.edu).

If you have questions about your rights or welfare as a participant, please contact the Oregon State University Institutional Review Board (IRB) Office, at (541) 737-8008 or by email at IRB@oregonstate.edu.

WHAT DOES MY SIGNATURE ON THIS CONSENT FORM MEAN?

Your signature indicates that this study has been explained to you, that your questions have been answered, and that you agree to take part in this study. You will receive a copy of this form.

Do not sign after the expiration date: 12/21/2019

Participant's Name (printed): ____

_______________________________________ ______________________________

(Signature of Participant) (Date)

_______________________________________ ______________________________

(Signature of Person Obtaining Consent) (Date)

APPENDIX C: HEALTH HISTORY QUESTIONNAIRE

Health History Screening Questionnaire

Study # _______ Participant ID _________ Date __________

Mark all *true* statements.

SECTION 1:

History:

Participant has had:

__ a heart attack
__ heart surgery
__ cardiac catheterization
__ coronary angioplasty (PTCA)
__ pacemaker/implantable cardiac defibrillator/rhythm disturbance
__ heart valve disease
__ heart failure
__ heart transplantation
__ congenital heart disease

Symptoms:

__ Participant has experienced chest discomfort with exertion.
__ Participant experiences unreasonable breathlessness.
__ Participant experiences dizziness, fainting, blackouts.
__ Participant takes heart medications.

Other health issues:

__ Participant has musculoskeletal problems.
__ Participant has concerns about the safety of exercise.
__ Participant takes prescription medication(s).
__ Participant is pregnant or lactating.

If any statements in this section are marked, a physician or appropriate health care provider should be consulted before engaging in exercise and documentation of this consultation should remain on file.

SECTION 2: CARDIOVASCULAR RISK FACTORS

__ Participant is a man older than 45 years.
__ Participant is a woman older than 55 years or has had a hysterectomy or is post-menopausal.
__ Participant smokes.
__ Participant's blood pressure is > 140/90.
__ Participant's blood pressure is not known.
__ Participant takes blood pressure medication.
__ Participant's blood cholesterol level is > 240 mg/dl.
__ Participant's cholesterol is not known.
__ Participant has a close blood relative who had a heart attack; before age 55 if father or brother or before age
65 if mother or sister.
__ Participant is physically inactive (< 30 minutes of physical activity on at least 3 days per week).
__ Participant is > 20 pounds overweight.

If 2 or more statements in this section are marked, a physician or appropriate health care provider *should be consulted before engaging in exercise and documentation of this consultation should remain on file.*

SECTION 3: NO HISTORY, SYMPTOMS, HEALTH ISSUES, OR CARDIOVASCULAR RISK FACTORS

__ None of the items in sections 1 and 2 above are true.

Participant should be able to exercise safely without consulting their healthcare provider.

Study Team Member Completing Form: ____

APPENDIX D: SUPPLEMENTAL HEALTH HISTORY

Subject # _______________ Date_____________

The purpose of this questionnaire is to obtain information regarding your health prior to conducting physiological testing. Please answer all questions to the best of your knowledge.

Thank you for your honest answers!

SECTION 1: ADDITIONAL HEALTH HISTORY

Are you a former smoker?
_______Yes If yes, please specify approximate quit date ___________________________
_______No

Are you diabetic?
_______Yes If yes, please specify list medications taken:
_______No

Do you have any respiratory problems (example: asthma, emphysema)?
_______Yes If yes, please specify:
_______No

Please explain any other significant medical problems that you consider it important for us to know:

Are you taking any supplements or over the counter mediations?
______Yes If yes, please list:
______No

Are you currently suffering from any cold, flu, or allergy symptoms?
_______Yes, please specify:
_______No

Do you ***currently*** have any muscular injury(s) that will prevent you from exercising?
_______Yes If yes, please explain the ***type of injury(s)*** and the ***length of time*** it has persisted:
_______No

Do you currently have any muscle or joint pain?
______ Yes If yes, is this pain mild, moderate or severe? (please circle one)
______ No Mild Moderate Severe

Have you had any muscular injury(s) in the ***past***?
_______Yes If yes, please report how long ago you had the injury(s):
_______No

Have you had any surgeries in the ***past***?
______ Yes If yes, please specify the type of surgery you have had, the year of surgery and
______ No your age at the time:

Do you ***currently*** have any bone or joint injury(s) that will prevent you from exercising?
_______Yes If yes, please report how long ago you had the injury(s):
_______No

Do you ***currently*** have any soft tissue injury(s) that would prevent you from exercising?
_______Yes If yes, please report how long ago you had the injury(s):
_______No

If you've ***recently*** (within the past 6 months) suffered any other type of injury(s) that prevent you from exercising? Please list them here.

Is there the **one** primary sport or physical activity you participate in?

Please list any other sports or physical activity you participate in regularly.

Please complete the following about your exercise program (if applicable):
Aerobic Exercise (e.g., running, swimming, biking, etc.):

Type of exercise	Minutes/Session	Intensity/Pace	Times/Week
a.	a.	a.	a.
b.	b.	b.	b.
c.	c.	c.	c.
d.	d.	d.	d.
e.	e.	e.	e.

Resistance Exercise _____________ ____________ _____________
Type of Training Minutes/session Times/Week

Do you intend to change your training status while participating in this study? ________________

How long have you participated in an aerobic exercise program? ________________

How long have you participated in a resistance exercise program? _______________

Females only:
What was the date of your last period? ____________________
Do you menstruate regularly?
________ Yes
________ No

Do you plan to become pregnant during the course of your participation in this study?
_______ Yes
_______ No

SECTION 2: EMERGENCY CONTACT

Please provide us with emergency contact information.

Name: ____ Relation:

____

Home/Cell Phone: _________________________________ Work Phone:

____

Study Team Member Completing Form:
____

APPENDIX E: PROPOSAL DOCUMENT

Addressing Error in the Cooper 12-Minute Run:
The Impact of Exercise Tolerance Parameters

Aaron Seipel

Oregon State University

Major Professor: Jason Penry, PhD

October 5th, 2016

TABLE OF CONTENTS

ABSTRACT

There is arguably no more common measure of an individual’s cardiorespiratory fitness than maximal oxygen consumption ($\dot{V}O_2$max). To most accurately assess $\dot{V}O_2$max, an individual’s gas consumption must be directly measured in a laboratory setting during a maximal graded exercise test (GXT). This testing requires specialized equipment and trained personnel, making it expensive and inaccessible to most individuals. To address this, easy to administer field tests have been developed to predict $\dot{V}O_2$max without the need for expensive equipment. Of these the Cooper 12-minute run (12MR) is one of the most commonly used and has shown the highest criterion-related validity among similar tests. That said, 12MR’s capability to predict $\dot{V}O_2$max is still only moderate at best. Looking at potential submaximal influences, critical speed (CS) and severe domain distance capacity (W’) can be used to describe an individual’s tolerance for high intensity endurance exercise, and thus have been shown to be predictors of endurance performance. The purpose of this study is to determine the extent to which error in 12MR-predicted $\dot{V}O_2$max can attributed to CS and W’. Thirty participants will complete a GXT, a 12MR, a series of exhaustive trials for CS and W’ determination, and a test for maximal aerobic speed (MAS). To eliminate any effect from a high $\dot{V}O_2$max, CS will be expressed as a proportion of MAS. The difference between 12MR-predicted and lab-measured $\dot{V}O_2$max values will be related to the CS/MAS quotient and W’ using a Pearson product moment correlation. The coefficient of determination will also be calculated for each of these relationships to determine the proportion of difference attributable to CS and W’.

INTRODUCTION

Maximal oxygen consumption ($\dot{V}O_2max$) is a strong predictor of endurance performance and functional capacity (McLaughlin et al., 2010; Shephard, 2008). $\dot{V}O_2max$ is a widely used measure across populations, and while direct laboratory testing may be popular amongst competitive endurance athletes, various indirect estimates of it are common in recreationally active individuals. While $\dot{V}O_2max$ may be measured in a performance lab setting, this testing requires specialized equipment and trained personnel, thus making it inaccessible to many individuals. As such, field tests with the ability to predict $\dot{V}O_2max$ independent of lab measures can serve as a valuable assessment tool. Of these, tests where an individual is asked to run for a set time or distance are particularly common due to their ease of administration. The Cooper 12-minute run (12MR) in particular has shown stronger criterion-related validity than similar tests of different duration (Mayorga-Vega et al., 2016). The prediction equation used with the 12MR however, assumes that the distance run during the test will only be affected by changes in $\dot{V}O_2max$, ignoring any effect from other variables related to performance (Cooper, 1968). Despite being better than many alternatives, the validity of the 12MR has been found to be moderate at best (Mayorga-Vega et al., 2016). While some work has been done assessing the application of 12MR to different populations, the effect of specific physiologic variables has been largely ignored. As such, factors that may contribute to error in the 12MR test should be assessed to determine its applicability to a wider range of individuals.

Two potential variables that may account for a substantial portion of 12MR error are critical speed (CS) and the severe domain distance capacity (W’). Critical speed is thought to represent the fastest speed at which an individual can achieve a steady-state $\dot{V}O_2$ and blood lactate concentration. At speeds above CS, W’ represents the finite distance that an individual is able to run before speed must be decreased (Jones et al., 2010). While regarding CS and W’ as distinct measures of aerobic and anaerobic capacity may be an overly simplified approach, Jones et al. (2010) contends that training aimed at increasing CS may be accompanied by concurrent decreases in W’. The cases cited in making this claim however, do not report a statistically significant interaction between the two variables (Jenkins & Quigley, 1992; Vanhatalo et al., 2008). Furthermore, both variables are predictors of tolerance to high intensity exercise (Bosquet et al., 2006; Jones et al., 2010; Kolbe et al., 1995). Given the relatively short duration of the 12MR, it is likely that both CS and W’ impact the distance an individual is able to run. The extent of the relative contributions of these two parameters on 12MR’s prediction of $\dot{V}O_2$max is unknown, as Cooper (1968) did not report these variables. Assessing the relationship between the lab-measured and 12MR-predicted $\dot{V}O_2$max difference and both CS and W’, will allow for a stronger understanding of their individual effects on $\dot{V}O_2$max prediction, and in turn, endurance performance. Further, it may help direct improvements in testing protocol and interpretation of results.

Problem Statement

The *objective* of this study is to examine the extent to which critical speed (CS) – expressed as a percentage of maximal aerobic speed (MAS) and the severe domain distance capacity (W’) – will describe the difference between Cooper 12-minute run (12MR) based and lab-measured $\dot{V}O_2$max values. Our *central hypothesis* is that both CS and W’ will show a direct positive relationship with the $\dot{V}O_2$max difference, with individuals with the largest CS and W’ demonstrating the greatest positive difference between the 12MR and laboratory measures.

Specific Aim and Hypothesis: This study will address our central hypothesis as follows:

Specific Aim #1. Examine the relationship between the CS/MAS quotient and the difference between 12MR-predicted $\dot{V}O_2$max and laboratory-measured $\dot{V}O_2$max. Our *hypothesis* is that the CS/MAS quotient will show a direct positive correlation with the difference between 12MR-predicted VO_2max and laboratory-measured VO_2max.

Specific Aim #2. Examine the relationship between W’ and the difference between 12MR-predicted $\dot{V}O_2$max and laboratory-measured $\dot{V}O_2$max. Our *hypothesis* is that W' will be directly and positively correlated and the difference between 12MR-predicted $\dot{V}O_2$max values and laboratory-measured VO_2max values. It is hypothesized that this correlation will not be as strong as the relationship between the CS/MAS quotient and the field and laboratory measures of VO_2max.

Assumptions

Participants will be capable of completing all of the tests within the set period of time. Moreover, participants will adhere to all pre-test instructions and general testing guidelines provided to them and provide a maximal effort during all testing.

Limitations

Due to the demanding nature of the study design, a higher attrition rate is anticipated. Environmental factors may affect performance during outdoor testing sessions. Study participation may not be kept entirely confidential due to the need to perform outdoor testing, which could lead to a self-selection bias among participants.

Delimitations

To increase the generalizability of results across sexes, both males and females will be tested., Due to time constraints limiting the number of subjects that may realistically be tested, this may limit the ability to test a large sample of either sex, which could impact the sensitivity to small effects. For safety reasons related to cardiovascular disease risk factors, only individuals between the ages of 18-35 will be tested, which may limit the generalizability of results. The results of this study will be specific to the Cooper 12-minute run and may not be applicable to other field tests.

Significance

Given that high levels of cardiorespiratory fitness are associated with numerous health benefits, as well as improved performance in endurance sport, tests of $\dot{V}O_2max$ serve as useful assessment tools. With laboratory testing expensive and inaccessible to many individuals, easy-to-administer field tests, like the 12MR (Cooper, 1968), have obvious appeal. It is important, however, that these tests are able to produce valid, consistent results across individuals. The criterion-related validity of the 12MR, despite being stronger than most other run/walk tests used to determine $\dot{V}O_2max$, is still only moderate at best (Mayorga-Vega et al., 2016). As such, factors leading to underestimation and overestimation by 12MR test results should be addressed, as these may serve useful in directing improvements to test protocol and interpretation of results.

The 12MR assumes that differences in distance run during the test are primarily attributable to difference in $\dot{V}O_2max$, with other variables having a negligible impact on performance. This simplified approach ignores basic mechanisms underlying fatigue and exercise tolerance during exercise in the severe intensity domain. At exercise intensities above CS, $\dot{V}O_2$ is unable to achieve steady state; H^+, P_i, and extracellular K^+ accumulate; and intramuscular [PCr] and glycogen are depleted. While the relative contribution to fatigue from each of these physiologic responses has not been resolved, their collective impact depletes the capacity for work above CS (W'), leading to exhaustion (Jones et al., 2010). The original data that the 12MR regression equation is based upon would have been influenced by subjects' CS and W'. As such, depending on an individual's CS and W' relative to these original subjects, individuals with lower or higher values would be expected to underestimate or overestimate $\dot{V}O_2max$, respectively. Cooper (1968) did not measure these parameters however, and thus the magnitude of their effect remains unknown. Examining the extent to which both CS and W' are related to the difference between 12MR-predicted $\dot{V}O_2max$ and lab-measured $\dot{V}O_2max$ will allow for more appropriate administration and interpretation of results from the 12MR test.

LITERATURE REVIEW

In assessing an individual's cardiorespiratory fitness, an individual's maximal rate of oxygen consumption, $\dot{V}O_2$max, is arguably the most common measure used. $\dot{V}O_2$max is a strong predictor of endurance performance and functional capacity (McLaughlin et al., 2010; Shephard, 2008), and thus can be used to track changes over time (Jones & Carter, 2000) or describe training intensity. As such, it is important to be able to obtain valid and reliable values when measuring $\dot{V}O_2$max. The gold standard determination of $\dot{V}O_2$max requires specialized equipment that is used to collect and analyze pulmonary gases in a laboratory setting during an incremental test. This makes direct $\dot{V}O_2$max measurement inaccessible to many individuals. As such, various field tests have been developed that are easy to administer and provide predictions of $\dot{V}O_2$max. While these field tests may not allow for direct measurement, investigating the extent to which different sources of error may impact $\dot{V}O_2$max prediction may help direct improvements in testing protocol. Following an overview of $\dot{V}O_2$max concepts, this review will focus specifically on the Cooper 12-minute run test (12MR). It will then introduce critical speed (CS) and severe domain distance capacity (W') as two potential variables that may contribute to error in $\dot{V}O_2$max prediction when using the 12MR.

Maximal Aerobic Power

The work of Taylor and colleagues (1955) first introduced $\dot{V}O_2$max as a measure for tracking improvements in cardiorespiratory fitness with training over time. Since then, it has been shown to be a strong predictor of endurance performance, as well as morbidity and mortality (McLaughlin et al., 2010; Myers et al., 2002; Yoshida et al., 1997).

Laboratory $\dot{V}O_2$max Assessment

The most accurate means of measuring $\dot{V}O_2$max is via an incremental exercise test, during which the test subject's pulmonary gases are collected and analyzed. These tests are common in performance lab settings and demonstrate high validity and reliability (Thoden, 1990). During the test, the intensity that the subject is working against is increased gradually at set intervals until volitional exhaustion is reached. The test is deemed maximal when a plateau in the rate ventilatory oxygen uptake ($\dot{V}O_2$) is observed despite an increase in workload. This plateau is defined as an increase in $\dot{V}O_2$ above the previous stage's workload of less than 2.1 mL/kg/min (Franklin, 2000). In the case that that this plateau is not observed, a respiratory exchange ratio (RER) greater than 1.15 (Franklin, 2000) and/or a heart rate (HR) reading within 10 beats per minute of the subject's age-predicted HR maximum (Poole et al., 2008) are commonly used as secondary criteria. While the use of secondary criteria may appear to address the problem of subjects not observing a 'maximal' result, Poole et al. (2008) found using RER > 1.15 underestimated $\dot{V}O_2$max by 16%, and HR criteria tended to exclude subjects that had demonstrated a $\dot{V}O_2$ plateau. Based upon this, Poole et al. (2008) proposed the use of a verification test stage in the absence of a $\dot{V}O_2$ plateau. Briefly, this involves the subject resting for a short period of time, then return to a workload slightly above the highest workload achieved during the initial test. The use of a verification stage was further investigated by Mier and colleagues (2012), who found $\dot{V}O_2$max values during this stage to not be significantly different than the $\dot{V}O_2$ values that did not plateau at the end of an initial graded exercise test. Taken together, these results support the use of a verification stage in the absence of a $\dot{V}O_2$ plateau, as opposed to using RER or HR as secondary criteria.

Maximal Aerobic Speed

Among other field tests proposed to predict $\dot{V}$O2max, is the Université de Montréal Track Test (UMTT; Léger & Boucher, 1980). Briefly, this test follows an incremental design during which the participant must run at progressively increasing speeds on a track until they are no long able to maintain the pace required for a given stage. Auditory signals are used for pacing purposes and sound at a cadence corresponding to when an individual should be reaching indicators placed at regular intervals along the track. Each stage is 2 minutes in duration and each incremental increase is intended to yield an increase in oxygen consumption of approximately 1 MET.

In their initial assessment of UMTT-predicted V̇O2max, Léger and Boucher (1980) observed no significant difference between predicted and actual values in two subgroups (61.5 ± 10.6 vs. 61.4 ± 10.9 mL/kg/min and 70.0 ± 4.5 vs 70.7 ± 6.0 mL/kg/min). Despite this, while one subgroup demonstrated an excellent correlation between the values ($r = 0.96$), the other subgroup showed only moderate strength ($r = 0.66$). While this leaves UMTT's ability to predict V̇O2max questionable, its utility is demonstrated by a strong correlation ($r = 0.80$) and no significant difference between final UMTT speed and the speed associated with maximal oxygen uptake, termed maximal aerobic speed (MAS; Berthoin et al., 1994; Berthoin et al., 1999). Maximal aerobic speed has been shown to be a strong predictor of performance in middle distance running performance used as part of a three-parameter model with CS and W' ($0.93 < r < 0.94$; Bosquet et al., 2006). Moreover, it can also be used in measuring critical speed (CS) to determine speeds used, and serves as a means of expressing CS as a proportion of maximal aerobic capacity (Billat et al., 1995; Schnitzler et al., 2010).

Field Testing: Cooper 12-Minute Run

With direct $\dot{V}O_2$max determination requiring specialized equipment that is either inaccessible or too expensive for most individuals, various field tests have been developed to provide a prediction of $\dot{V}O_2$max (Cooper, 1968; Léger & Boucher, 1980; Léger & Lambert, 1982).

Of the field tests for $\dot{V}O_2$max prediction, the 12MR (Cooper, 1968) is one of the most commonly used. The test assumes a maximal effort and provides a prediction of $\dot{V}O_2$max based upon the distance an individual is able to run in a 12-minute period. This prediction is derived from regression data collected from 115 male US Air Force officers whose distance run was related to $\dot{V}O_2$max determined using an incremental test. Additional physiologic measures that may have impacted performance were not reported.

Validity and Reliability

In a recent meta-analysis of run/walk field tests, Mayorga-Vega and colleagues (2016) assessed criterion-related validity of the 12MR using a Pearson's zero-order correlation coefficient (*r*). Of the tests included, 12MR showed the strongest correlation with $\dot{V}O_2$max (*r* = 0.78, 0.72-0.83). Of the studies included in this meta-analysis, the magnitude of the error associated with 12MR differed greatly. Bandyopadhyay (2015) found 12MR to overestimate $\dot{V}O_2$max by a mean of 3.0 mL/kg/min in male university students, yet found it to underestimate $\dot{V}O_2$max by a mean of 3.7 mL/kg/min in female students (Bandyopathy, 2014). Bland-Altman analysis revealed large limits of agreement in each of these cases, suggesting that the 12MR prediction was inappropriate for the subjects tested. A separate study in young obese individuals found 12MR to underestimate $\dot{V}O_2$peak by a mean of 6.71 mL/kg/min (Quinart et al., 2014). The use of $\dot{V}O_2$peak in this case however, indicates that a plateau in the rate of oxygen consumption was not observed in all subjects. This suggests that the true difference between the 12MR prediction and $\dot{V}O_2$max would have been greater than the reported difference.

Sources of Error

Due to the often uncontrollable circumstances surrounding field testing and lack of direct measurement, greater variance in results is to be expected. While obvious factors that will impact the majority of run performance tasks should be accounted for (e.g. weather conditions, participant pre-exercise fatigue levels, etc.), to best minimize the variance in 12MR prediction, additional interactions between variables should be considered.

With the initial regression that the 12MR prediction is based upon determined exclusively in young to middle-aged active men (Cooper, 1968), its generalizability across populations has been questioned. Of the factors that may influence this, sex and aerobic fitness level are two of the most commonly considered measures and have produced conflicting results. In examining sex differences across a range of studies, Safrit et al. (1988) found 77% of the variance in scores to be attributable to statistical artifacts and sampling error. In men however, this only addressed 38% of the variance, suggesting superior generalizability of the test results in women. More recently, Mayorga-Vega et al. (2016) reported that the criterion-related validity of walk/run tests was unaffected by sex. It is important to note however, that due to a limited number of published studies examining 12MR criterion-related validity based on sex, both of these analyses grouped 12MR with several other walk/run field assessments. While this approach may be appropriate tests of similar duration (≥ 9 min; Safrit et al., 1988), it is likely inappropriate across a wider range (0.25 mile – 5000 meters; Mayorga-Vega et al., 2016), and could explain these discrepancies.

Using a G-study model, Penry et al. (2011) found the greatest systematic error variance in the 12MR to be attributable to subject-test occasion interactions (4.3%), followed by three-way interaction between subject, test occasion, and instrument (3.8%). In this case, Bland-Altman analysis of the 12MR prediction showed a trend towards underestimation and overestimation in individuals with lower or higher $\dot{V}O_2max$ values, respectively. The authors suggested that this trend was related to psychological factors and familiarity with running having a more pronounced effect in less aerobically fit individuals (Penry et al. 2011). It is also possible that having to pace the test based upon a time parameter as opposed to a measured distance could influence results (McNaughton et al. 1998), as more aerobically fit individuals demonstrated slightly lower test-retest variability (Penry et al. 2011). Similar to their assessment of sex effects, Mayorga-Vega et al. (2016) found no effect on criterion-related validity attributable to higher or lower $\dot{V}O_2max$ values, but again, their approach generalized the results of all walk/run field tests – an inappropriate means of evaluating the effect of aerobic fitness in a single field test. Further, if an effect from maximal oxygen uptake did exist, its observable magnitude could be dampened due to the authors including studies that used $\dot{V}O_2$peak in place of $\dot{V}O_2$max in their analysis. As such, the present research does not preclude from the realm of possibility an effect by measures of aerobic fitness on 12MR predictions.

Addressing Concerns

Some cases showing strong relationships between the 12MR prediction and $\dot{V}O_2$max, despite over or underestimation, have derived new population-specific predictive regression equations (Bandyopthy, 2014; Bandyopathy, 2015; Quinart et al., 2014). Few however, have sought to understand and address the mechanisms underlying these discrepancies. Given that when introducing the 12MR, Cooper (1968) did not report any physiologic parameters of aerobic or anaerobic fitness besides $\dot{V}O_2$max, the prediction equation assumes that other variables have a negligible impact on performance. This assumption ignores our present understanding of fatigue and exercise tolerance during exercise in the severe intensity domain. As such, factors influencing performance independent of $\dot{V}O_2$max would lead an individual to under or overestimate their $\dot{V}O_2$max as a function of their difference from the mean levels in the original data. Of particular interest with regards to high intensity exercise tolerance are the critical speed (CS) and severe domain distance capacity (W’) concepts (Jones et al., 2010).

Critical Speed and Severe Domain Distance Capacity

Initially introduced for intermittent isometric contractions, the power–time to exhaustion (P–TE) relationship is linear and inverse during exercise in the severe intensity domain (Monod & Scherrer, 1965). In applying these observations to whole body dynamic exercise, this relationship has been shown to exist and investigated extensively in the cycling literature (Jones et al., 2010; Moritani et al., 1981). The early advent of the P–TE relationship in cycling is largely attributable to the capability of cycling power meters to directly monitor workload. With quantifying power output only feasible during certain endurance exercise modalities however, the same principles have also been applied to activities like running and swimming using speed measures rather than power data (Hughson et al., 1984; Wakayoshi et al., 1992). Given the applicability of the P–TE relationship to modalities utilizing differing metrics and terminology, the remainder of this section will use critical intensity (CI) to describe generalizable concepts, and CS/CP in citing specific examples.

Based upon the linear and inverse relationship described, for a given intensity (I), time to exhaustion (TE) can be represented by the following equation:

$$I = (W' / TE) + CI$$

As written, W' represents the work that can be performed at intensities greater than CI, while CI is given by the asymptote of the I–TE curve (Hughson et al., 1984; Jones et al., 2010). From a purely mathematical standpoint, CI thus represents an intensity that can be maintained for an infinite amount of time without the development of fatigue. The possibility of a speed or workload that can be maintained indefinitely however violates basic physiologic principle, and thus TE at CI may be relatively short in practice. In examining the physiologic profile of running at CS determined from various predictive models, Bull et al. (2008) found that many runners reached volitional exhaustion in less than an hour. Similarly in elite cyclists, McClave et al. (2011) found that CP did not represent a sustainable workload, with an average time to exhaustion to be only 14.79 ± 8.38 minutes. As such, while CI may be defined as the highest intensity at which a steady state $\dot{V}O_2$ and blood lactate concentration can be achieved (Poole et al., 1988), fatigue cannot be solely attributed to work done above CI. Rather, CI may represent a critical neuromuscular fatigue threshold above which exhaustion is predominantly the result of peripheral mechanisms of fatigue (Burnley et al., 2012; Poole et al., 2016).

Mechanistic Basis

With CI and W' determined using performance outcomes as opposed to the measurement of some specific physiologic variable, there may not be a single underlying mechanism that they can be attributed to (Jones et al., 2010). Early work found constant workload cycling performed at 5% of maximal aerobic power below CP to elicit a steady state response in $\dot{V}O_2$ and blood lactate concentration ([BLC]). Conversely, workloads 5% above CP led to a progressive increase in [BLC] and $\dot{V}O_2$, suggesting that CP represents the highest workload at which physiologic steady state can be achieved (Poole et al., 1988). As such, much work has sought to address the cause of these increases. Rossiter et al. (2002) used whole body magnetic resonance spectroscopy to compare the response of muscle phosphocreatine ([PCr]) dynamics to the $\dot{V}O_2$ response seen with high intensity exercise. Depletion of muscle [PCr] was found to be closely related to increases in $\dot{V}O_2$ during high intensity exercise. With these increases in $\dot{V}O_2$ related to [PCr], and with them ultimately being truncated at $\dot{V}O_2$max, TE and W' during severe intensity exercise may be described by metabolic control processes (Burnley & Jones, 2007; Jones et al., 2010). Further evidence suggests that the magnitude of W' may also be related to intramuscular glycogen concentrations (Miura et al., 2000).

Most recently, Vanhatalo et al. (2016) expanded upon the protocol used by Poole et al. (1988) to produce a more complete profile of metabolic responses above and below CP. Constant load cycling trials were performed at 5% of maximal aerobic power both above (CP+5%) and below (CP-5%) CP. An additional trial was also performed at the same workload as CP-5%, but equal in duration to CP+5% (~12 min; $CP+5\%_{isotime}$). End-exercise levels of [PCr], [Cr], $[La^-]$, and pH for CP+5% differed from both CP-5% and $CP+5\%_{isotime}$. CP-5% and $CP+5\%_{isotime}$ however, did not differ in any of these variables, suggesting a steady state response below, but not above CP.

Vanhatalo et a. (2016) also studied biopsies taken from the vastus lateralis muscle of a subset of subjects. This examination found a positive correlation between CP and the proportion of type I muscle fibers, suggesting reliance on predominately oxidative pathways. No distinct relationship however, was observed between muscle fiber type and the magnitude of W', suggesting a contribution from both oxidative and non-oxidative pathways.

Performance Implications

Given their relevance to the power-TE relationship, CP (or CS) and W’ have been investigated with respect to various performance measures. Kolbe et al. (1995) examined the relationship between CS and running times for distances ranging from 1-km to 21.1km, with moderate correlation observed (r = -0.75 to -0.85). While these values may lack that sensitivity to accurately predict run times, across distances they were at least as strong as the correlation between run time and $\dot{V}O_2$max (r = -0.75 to -0.81) In a separate study, where 800-m run time predicted by the CS curve was compared to actual 800-m run performance, similarly strong correlations were found (r = 0.83 to 0.94; Bosquet et al., 2006). The range of correlation values in this case was due to various CS values being determined using different models. Following this work up, when W’ was compared to 800-m run speed, no correlation between the two was found (r = -0.07 to 0.23) regardless of the model used (Bosquet et al, 2007). These findings may be reconciled by evidence suggesting that training techniques focused on increasing CS, may lead to slight reductions in W’ (Jenkins & Quigley, 1992; Vanhatalo et al, 2008). These observations, however, were not statistically significant, and may require further investigation. Had interaction occurred between CS and W’ though, in tasks with a strong reliance on oxidative pathways, a weak correlation between W’ and performance would be expected.

With the bulk of these data supporting CS as an important predictor of performance, Jones et al (2010) suggest that for an individual to achieve optimal endurance performance, the entirety of the task must be performed at or above CS. In this case, the individual running would be expected to run at CS, fully deplete W’ at some point, and return to CS for the remainder of the run post-depletion. With the CS-TE model based purely on a controlled mathematical approach to the scenario however, there is evidence to suggest that it may not be a realistic strategy. While in theory CS represents a fatigueless intensity, several studies have produced results conflicting with this assumption. In testing elite cyclists, McClave et al (2011) found CP to be sustainable for only 14.79 ± 8.38 minutes. Similarly, upon examining moderately trained runners, Bull et al (2008) found CS predictions from various models to be unsustainable across subjects. Only half of their subjects in this case were able to complete a 60-min constant speed trial at the lowest predicted CS value. These findings may in part be explained by recent work that found CP to consistently overestimate maximal lactate steady state (Mattioni Maturana et al, 2016). Conversely, Smith and Jones (2001) found no difference between CS and speed at maximal lactate steady state. While these findings may conflict, they do not necessarily invalidate CI as a predictor of performance. Rather, they simply suggest that more refined modeling techniques should be considered in future work.

Determination

Traditionally in determining CS and W’, an individual must complete 4-6 constant speed trials to exhaustion (Hughson et al, 1984). Speeds for these trials should aim to elicit exhaustion between 1-10 minutes, and have been determined in different ways across studies. In early work, these were standard across subjects based on expectation from previous performances (Hughson et al, 1984). More recently, these speeds have been set at various percentages of estimated $\dot{V}O_2$max speed or previously determined MAS (Bosquet et al, 2006; Bull et al, 2008; Smith & Jones, 2001). Time to exhaustion for these trials is then plotted with respect to speed, and linear regression is used to determine the line of best fit (Hughson et al, 1984). The slope of this line represents W’, whereas the y-intercept represents CS. While this method is standard across much of the literature, Morton (1996) proposed a 3-parameter model for determining CP and W’ that incorporates MAS into its prediction as follows:

$$TE = [W'/(S - CS) - W'/(MAS - CS)]$$

While not as widely used, there is some evidence that the 3-parameter model may predict a more sustainable intensity for CS (Bull et al, 2008).

It should be noted that in the cycling literature, a 3-minute all-out test has been introduced that is able to accurately predict CP and W’ (Vanhatalo et al, 2008). A similar test has been applied to running, and though it provides a good prediction in most individuals, Bland-Altman analysis reveals an uneven bias, with less aerobically fit individuals tending to score higher on the 3-minute run than on the exhaustive treadmill trials (Maryn et al., *in preparation for publication*)

MATERIALS AND METHODS

Participants

Participants for this study will be between 18 and 35 years old, and will be recruited from the mid-Willamette valley via fliers, social media, email announcements on local running and triathlon club list-serves, and word of mouth advertising. Approximately 30 participants will be recruited for this study, with approximately 15 males and 15 females participating. Individuals across a range of fitness levels will be recruited to participate, but all individuals must be capable of running a minimum of 30 minutes without stopping to ensure that they are able to complete the necessary testing protocol. Prior to their participation in the study, all participants will complete a health and running experience/injury history questionnaire to assess cardiac risk. Any individuals presenting with more than one cardiovascular disease risk factors, as outlined by ACSM’s risk stratification guidelines, will be excluded from participating in the study (Franklin, 2000). Individuals will also be excluded if they have any current or past injury or illness that would presently prevent them from returning to their pre-injury/illness training volume and/or intensity.

Prior to initiation of this study, approval for all procedures will be obtained from the Oregon State University Institutional Review Board (IRB). Prior their involvement in this study, informed consent will be obtained from all potential participants.

Instruments

A ParvoMedics TrueMax 2400 metabolic cart will be used to assess $\dot{V}O_2$ (ParvoMedics, Sandy, UT) will be used. A Polar heart rate (HR) monitor (Polar, Lake Success, NY) will be used to measure HR. Tests for $\dot{V}O_2$max and CS will be conducted on a TrackMaster treadmill (Full Vision, Newton, KS). An InBody 770 bioelectrical impedance analysis system (InBody, Cerritos, CA) will be used to assess body composition for descriptive purposes.

Procedures

Each participant will visit the Oregon State University Human Performance Lab three times and a standard 400-meter running track in the Corvallis area two times. During the lab visits, participants will perform one maximal graded exercise test (GXT_{max}) to determine $\dot{V}O_2$max, and a series of six runs to exhaustion over the course of two visits to determine critical speed (CS) and supra-CS distance capacity (W’). Participants will perform one test during each track visit: one 12MR and one maximal aerobic speed (MAS) test. During all assessments, testing data will be hidden from participant view; however, participants will be verbally encouraged during all trials. Participants will perform the 12MR during their first visit, to establish a baseline fitness level for subsequent test starting intensities. The order of the remaining four testing sessions will be randomized to minimize any effect of previous testing. During the first visit, participants will complete an informed consent form at the track, followed by a health and running history questionnaire for initial screening. During the day of the first lab test, participant height, weight, and body composition via InBody 770 test will be determined prior to other testing procedures.

During lab testing, environmental conditions will be maintained at approximately 22 degrees Celsius and approximately 30% humidity. Barometric pressure will be noted at the beginning of each testing session, as these data are necessary for flow and gas calibration purposes. Temperature, humidity, wind speed, barometric pressure, and precipitation will be recorded prior to all track tests. In the case that there is concern that environmental factors may negatively impact performance, testing will be rescheduled for a later date. Environmental conditions that would warrant rescheduling testing will be considered any of the following: temperatures below 10 or exceeding 24 degrees Celsius, humidity less than 20% or greater than 70%, and wind speeds above 5 kilometers per hour.

Maximal Graded Exercise Test: Prior to the GXT_{max}, participants will be fitted with a nose clip and mask equipped with two one-way valves connected to the metabolic cart, to allow for the collection of expired gases throughout the test. Participants will then perform a 3-minute warm-up at a 0% gradient. Starting speed will be estimated based upon 12MR performance and will range from 8.0 to 11.0 km/hr with the goal of having the test last between 12 and 15 minutes. Following this warm-up, grade will be increased to 3%, signifying the start of the test. Stages will be set at 1 minute in duration, with speed or incline increased at the end of each stage. Rating of perceived exertion (RPE) will be collected halfway through each stage (Borg, 1982). Speed will be adjusted first and will be increased by 0.8 km/hr at the end of every minute until the participant reaches a RPE of 13. From this point, speed will be kept constant and incline will be increased by 1% grade at the end of each stage until the participant indicates that he/she is unable to continue. Immediately following the final stage of the test, participants will be encouraged to walk at an easy pace to ensure appropriate cool down.

For the test to be considered maximal, participants will need to exhibit an increase of less than 2.1 mL/kg/min in minute oxygen consumption across the final two stages. If this plateau is achieved, $\dot{V}O_2max$ will be taken as the maximum value recorded for a completed stage during the test. In the event that a plateau is not achieved, a verification stage will be performed. Following a 10-minute cool-down period, speed and incline will gradually be increased over the next two minutes to the intensity reached during the final stage of the GXT_{max}. After one minute at this intensity, incline will be increased by 1% grade and the participant will be encouraged to maintain this intensity for two minutes. If they are able to maintain at least one minute at this intensity and the final minute-averaged $\dot{V}O_2$ value obtained is within 2.1 mL/kg/min of the final value obtained during the initial test, a plateau will have been achieved. If they are unable to sustain one minute at this intensity, these data may not be used and the participant must be excluded from the remainder of the study. If the participant completes the full 2 minutes at the increased intensity and a plateau in oxygen consumption is not observed, another 10-minute cool-down will be performed and the verification stage protocol will be repeated, but with an increase of 2% grade instead. The maximum $\dot{V}O_2$ value recorded during these verification trials will be considered a participant's $\dot{V}O_2$max.

Prior to testing, calibrations will be performed for gas exchange using a known O_2–CO_2 mixture, and for flow rate using a known-volume syringe. All $\dot{V}O_2$ values will be normalized by dividing absolute oxygen consumption by the participant's mass.

Critical Speed: To determine CS and W’, the procedures described in Hughson et al. (1984) will be employed. Over two testing days, participants will perform six runs to volitional fatigue at different speeds on the treadmill, with speeds for these trials intended to elicit exhaustion between one and 10 minutes. Speeds will be approximated based upon 12MR performance. Prior to testing, subjects will be allowed a 10-minute period at a self-selected warm-up speed. Speed on this warm-up may not exceed 70% of the participant’s speed during the 12MR. Trial order will be randomized and time to exhaustion recorded for each trial. Participants will rest between trials and will be considered adequately recovered when their HR reaches a value within 20 beats per minute of pre-exercise heart rate. To determine CS, the speed of each individual trial will be plotted against the inverse of time to exhaustion for the respective trial. The y-intercept of the line of best fit for each plot will be taken as that participant’s CS, and will be determined using linear regression. The slope of this line will represent the value of W’. CS will be expressed as a percentage of MAS, described below.

Maximal Aerobic Speed: To determine MAS, the protocol describe by Léger and Boucher (1980) for the Université de Montréal track test (UMTT) will be adapted to be performed on a standard 400-meter outdoor track. Large marker cones will be placed along the track's infield next to the inside lane at 50-meter intervals. Additional smaller cones will be placed 30 feet before each of the larger cones. Participants will be paced by a whistle signal at the times they should be passing each large cone for a given pace. Prior to testing, subjects will be allowed a 10-minute warm-up period at a self-selected speed. Starting pace will be estimated based upon 12MR performance and will range from 8.0 to 14.0 kilometers per hour, with the goal of having the test last between 12 and 16 minutes. This test will be continuous and is intended to be maximal, with stages set at 2 minutes in duration and pace increasing by 1 kilometer per hour every stage. The test will be terminated when the participant indicates that they are unable to continue or when they have not reached the small cone preceding the pace cone that they should have reached. Immediately following the final stage of the test, participants will be encouraged to walk at an easy pace to ensure appropriate cool down. The speed of the final completed stage will be taken as the participant's MAS.

Cooper 12-Minute Run: The 12MR will be performed on a standard 400-meter outdoor track, as described by Cooper (1968). Prior to testing, participants may perform a 10-minute warm-up at a self-selected speed, but will be instructed to refrain from any sprinting or other high-intensity running. Participants will be instructed to complete as many laps as possible within a 12-minute time period. It will be emphasized that the test is intended to be completed at a maximal effort, but that participants should try to adopt a pacing strategy that will not cause premature fatigue or inability to complete the test. Time will be recorded for each participant at 400-meter intervals, with any substantial changes in pacing noted. The test administrator will record the number of laps completed and will indicate the elapsed time at 3, 6, and 9 minutes into the test. Participants will otherwise be blinded to time and will not be permitted to wear a watch. When the 12-minute period is complete, participants will be instructed to stop immediately, and the distance completed for the current lap will be determined using a measuring wheel. Once this distance has been measured, participants will be encouraged to walk or run at an easy pace to ensure appropriate cool down. The total distance run by the participant will then be used to predict $\dot{V}O_2$max using the prediction equation derived by Cooper (1968).

General Considerations: Participants will be required to refrain from structured exercise in the 24 hours prior to testing. With the exception of water, participants will be required to refrain from consuming food or drink in the 2 hours prior to testing. Adherence to these requirements will be verified at the beginning of each visit by self-report. In the event that a participant has exercised or consumed food or drink within this period of time, the testing session will be rescheduled for a later time and/or date. Each participant must complete all testing within a 6-week time frame, although they will be encouraged to complete it within 3-4 weeks so as to minimize any training effect. All testing sessions will be separated by a minimum of 48 hours.

Statistical Analysis

All statistical analyses will be performed using SPSS Statistics 22 (IBM, Armonk, NY).

Descriptive Statistics: Mean and standard deviation will be calculated for all descriptive data (age, height, weight, percent body fat, absolute CS and CS relative to MAS, W’, and $\dot{V}O_2$max).

Analytic Statistics: $\dot{V}O_2$max difference will be measured in terms of 12MR $\dot{V}O_2$max minus lab determined $\dot{V}O_2$max. Pearson product moment correlation will be used to assess the magnitude and directionality of the $\dot{V}O_2$max difference-CS/MAS quotient and $\dot{V}O_2$max difference-W’ relationships. Pearson product moment correlation will also be calculated to assess the CS/MAS quotient-W’ relationship, as well as the CS/MAS quotient- and W’- 12MR relationships. The coefficient of determination will be calculated for each of these relationships to assess the proportion of variance in $\dot{V}O_2$max difference attributable to the

CS/MAS quotient and W’. Multiple regression will also be used to determine any interaction effect between CS/MAS and W’ (α = 0.05).

REFERENCES

Bandyopadhyay, A. (2014). Validity of Cooper's 12-min run test for estimation of maximum oxygen uptake in female university students. *Indian Journal of Physiology and Pharmacology*, *58*(2), 184–186.

Bandyopadhyay, A. (2015). Validity of Cooper's 12-minute run test for estimation of maximum oxygen uptake in male university students. *Biology of Sport*, *32*(1), 59–63. http://doi.org/10.5604/20831862.1127283

Berthoin, S., Gerbeaux, M., Turpin, E., Guerrin, F., Lensel-Corbeil, G., & Vandendorpe, F. (1994). Comparison of two field tests to estimate maximum aerobic speed. *Journal of Sports Sciences*, *12*(4), 355–362. http://doi.org/10.1080/02640419408732181

Berthoin, S., Baquet, G., Rabita, J., Blondel, N., Lensel-Corbeil, G., & Gerbeaux, M. (1999). Validity of the Université de Montréal Track Test to assess the velocity associated with peak oxygen uptake for adolescents. *The Journal of Sports Medicine and Physical Fitness*, *39*(2), 107–112.

Billat, L. V., & Koralsztein, J. P. (1996). Significance of the velocity at VO2max and time to exhaustion at this velocity. *Sports Medicine (Auckland, N.Z.)*, *22*(2), 90–108.

Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine and Science in Sports and Exercise*, *14*(5), 377–381.

Bosquet, L., Duchene, A., Lecot, F., Dupont, G., & Leger, L. (2006). Vmax estimate from three-parameter critical velocity models: validity and impact on 800 m running performance prediction. *European Journal of Applied Physiology*, *97*(1), 34–42. http://doi.org/10.1007/s00421-006-0143-7

Bosquet, L., Delhors, P. R., Duchene, A., Dupont, G., & Leger, L. (2007). Anaerobic running capacity determined from a 3-parameter systems model: relationship with other anaerobic indices and with running performance in the 800 m-run. *International Journal of Sports Medicine*, *28*(6), 495–500. http://doi.org/10.1055/s-2006-924516

Bull, A. J., Housh, T. J., Johnson, G. O., & Rana, S. R. (2008). Physiological responses at five estimates of critical velocity. *European Journal of Applied Physiology*, *102*(6), 711–720. http://doi.org/10.1007/s00421-007-0649-7

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

Cooper, K. H. (1968). A means of assessing maximal oxygen intake. Correlation between field and treadmill testing. *JAMA*, *203*(3), 201–204.

Franklin, B. A. (Ed.). *ACSM's guidelines for exercise testing and prescription*. Philadelphia, PA: Lippincott, Williams & Wilkins. 2000.

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A high velocity treadmill running test to assess endurance running potential. *International Journal of Sports Medicine*, *5*(1), 23–25. http://doi.org/10.1055/s-2008-1025875

Jenkins, D. G., & Quigley, B. M. (1992). Endurance training enhances critical power. *Medicine and Science in Sports and Exercise*, *24*(11), 1283–1289.

Jones, A. M., & Carter, H. (2000). The effect of endurance training on parameters of aerobic fitness. *Sports Medicine (Auckland, N.Z.)*, *29*(6), 373–386.

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: implications for determination of $\dot{V}O_2$max and exercise tolerance. *Medicine and Science in Sports and Exercise*, *42*(10), 1876–1890. http://doi.org/10.1249/MSS.0b013e3181d9cf7f

Léger, L., & Boucher, R. (1980). An indirect continuous running multistage field test: the Université de Montréal track test. *Canadian Journal of Applied Sport Sciences. Journal Canadien Des Sciences Appliquées Au Sport*, *5*(2), 77–84.

Léger, L. A., & Lambert, J. (1982). A maximal multistage 20-m shuttle run test to predict VO2 max. *European Journal of Applied Physiology and Occupational Physiology*, *49*(1), 1–12.

Mattioni Maturana, F., Keir, D. A., McLay, K. M., & Murias, J. M. (2016). Can measures of critical power precisely estimate the maximal metabolic steady state? Applied Physiology, Nutrition, and Metabolism. http://doi.org/10.1139/apnm-2016-0248

Mayorga-Vega, D., Bocanegra-Parrilla, R., Ornelas, M., & Viciana, J. (2016). Criterion-Related Validity of the Distance- and Time-Based Walk/Run Field Tests for Estimating Cardiorespiratory Fitness: A Systematic Review and Meta-Analysis. *PloS One*, *11*(3), e0151671. http://doi.org/10.1371/journal.pone.0151671

McLaughlin, J. E., Howley, E. T., Bassett, D. R., Thompson, D. L., & Fitzhugh, E. C. (2010). Test of the classic model for predicting endurance running performance. *Medicine and Science in Sports and Exercise*, *42*(5), 991–997. http://doi.org/10.1249/MSS.0b013e3181c0669d

McNaughton, L., Hall, P., & Cooley, D. (1998). Validation of several methods of estimating maximal oxygen uptake in young men. *Perceptual and Motor Skills*, *87*(2), 575–584. http://doi.org/10.2466/pms.1998.87.2.575

Mier, C. M., Alexander, R. P., & Mageean, A. L. (2012). Achievement of VO2max criteria during a continuous graded exercise test and a verification stage performed by college athletes. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *26*(10), 2648–2654. http://doi.org/10.1519/JSC.0b013e31823f8de9

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

Monod, H., & Scherrer, J. (1965). The Work Capacity of a Synergic Muscular Group. *Ergonomics*, *8*(3), 329–338. http://doi.org/10.1080/00140136508930810

Moritani, T., Nagata, A., Devries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24(5), 339–350. http://doi.org/10.1080/00140138108924856

Myers, J., Prakash, M., Froelicher, V., Do, D., Partington, S., & Atwood, J. E. (2002). Exercise Capacity and Mortality among Men Referred for Exercise Testing. New England Journal of Medicine, 346(11), 793–801. http://doi.org/10.1056/NEJMoa011858

Penry, J. T., Wilcox, A. R., & Yun, J. (2011). Validity and reliability analysis of Cooper's 12-minute run and the multistage shuttle run in healthy adults. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *25*(3), 597–605. http://doi.org/10.1519/JSC.0b013e3181cc2423

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016). Critical Power: An Important Fatigue Threshold in Exercise Physiology. Medicine and Science in Sports and Exercise. http://doi.org/10.1249/MSS.0000000000000939

Poole, D. C., Ward, S. A., Gardner, G. W., & Whipp, B. J. (1988). Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics*, *31*(9), 1265–1279. http://doi.org/10.1080/00140138808966766

Poole, D. C., Wilkerson, D. P., & Jones, A. M. (2008). Validity of criteria for establishing maximal O2 uptake during ramp exercise tests. *European Journal of Applied Physiology*, *102*(4), 403–410. http://doi.org/10.1007/s00421-007-0596-3

Quinart, S., Mougin, F., Simon-Rigaud, M.-L., Nicolet-Guénat, M., Nègre, V., & Regnard, J. (2014). Evaluation of cardiorespiratory fitness using three field tests in obese adolescents: validity, sensitivity and prediction of peak VO2. *Journal of Science and Medicine in Sport / Sports Medicine Australia*, *17*(5), 521–525. http://doi.org/10.1016/j.jsams.2013.07.010

Rossiter, H. B., Ward, S. A., Kowalchuk, J. M., Howe, F. A., Griffiths, J. R., & Whipp, B. J. (2002). Dynamic asymmetry of phosphocreatine concentration and O2 uptake between the on- and off-transients of moderate- and high-intensity exercise in humans. *The Journal of Physiology*, *541*(Pt 3), 991–1002. http://doi.org/10.1113/jphysiol.2001.012910

Safrit, M. J., Glaucia Costa, M., Hooper, L. M., Patterson, P., & Ehlert, S. A. (1988). The validity generalization of distance run tests. *Canadian Journal of Sport Sciences = Journal Canadien Des Sciences Du Sport*, *13*(4), 188–196.

Schnitzler, C., Heck, G., Chatard, J.-C., & Ernwein, V. (2010). A simple field test to assess endurance in inexperienced runners. *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, *24*(8), 2026–2031. http://doi.org/10.1519/JSC.0b013e3181d2c48d

Shephard, R. J. (2009). Maximal oxygen intake and independence in old age. *British Journal of Sports Medicine*, *43*(5), 342–346. http://doi.org/10.1136/bjsm.2007.044800

Smith, C. G., & Jones, A. M. (2001). The relationship between critical velocity, maximal lactate steady-state velocity and lactate turnpoint velocity in runners. *European Journal of Applied Physiology*, *85*(1-2), 19–26.

Taylor, H. L., Buskirk, E., & Henschel, A. (1955). Maximal Oxygen Intake as an Objective Measure of Cardio-Respiratory Performance. *Journal of Applied Physiology*, *8*(1), 73–80.

Thoden, J. S. Testing aerobic power. In: J.D. MacDougall, H.A. Wenger, and H.J. Green (Eds.), *Physiological Testing of the High-Performance Athlete*. Champaign, IL: Human Kinetics, 1990. pp. 107-74.

Vanhatalo, A., Black, M. I., DiMenna, F. J., Blackwell, J. R., Schmidt, J. F., Thompson, C., … Jones, A. M. (2016). The mechanistic bases of the power-time relationship: muscle metabolic responses and relationships to muscle fibre type. *The Journal of Physiology*. http://doi.org/10.1113/JP271879

Vanhatalo, A., Doust, J. H., & Burnley, M. (2008). A 3-min all-out cycling test is sensitive to a change in critical power. *Medicine and Science in Sports and Exercise*, *40*(9), 1693–1699. http://doi.org/10.1249/MSS.0b013e318177871a

Wakayoshi, K., Ikuta, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Determination and validity of critical velocity as an index of swimming performance in the competitive swimmer. *European Journal of Applied Physiology and Occupational Physiology*, *64*(2), 153–157.

Yoshida, T., Udo, M., Iwai, K., & Yamaguchi, T. (1993). Physiological characteristics related to endurance running performance in female distance runners. *Journal of Sports Sciences*, *11*(1), 57–62. http://doi.org/10.1080/02640419308729964