Validity of a stationary cycling protocol for tracking changes in uphill cycling time-trial performance
by Owen Frederic Murphy

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
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Montana State University
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Abstract:

The ability to accurately quantify and predict endurance performance is imperative when assessing the effects of training interventions, dietary regimes, equipment modifications, and/or alterations in athlete position or technique. Due to the invasive nature and excessive costs of traditional physiological and biomechanical determinants of endurance performance, performance-based determinants of performance have received considerable attention.

The purpose of the present study was to determine the reliability and validity of a scaling-derived cycle ergometer protocol (SDP) for tracking changes in uphill time-trial (TT) cycling performance. Phase I of the study assessed the reliability of the Scaling Derived Protocol (SDP) via the administration of three SDP protocols within a ten-day time period. Phase II of the study determined the ability of the SDP to track longitudinal changes in uphill time-trial performance. Local competitive cyclists participated in either two or three testing periods separated by a minimum of ten weeks (May, July, September 2001). Each testing period consisted of an outdoor uphill TT (5-km, 8% grade) followed within ten days by a laboratory-based SDP. Longitudinal inter-trial changes in average TT speed (m/s) were compared with longitudinal inter-trial changes in SDP time-to-exhaustion (TTE, min) and relative SDP maximal power output (W_{max} , watts kg^{-1}).

There were no significant Phase I inter-trial differences for time-to-exhaustion, maximum power output, maximum heart rate, and relative VO_{2max} . Intraclass correlation coefficients were high for all variables, ranging from $R = 0.933$ to 0.992 . Single-score reliability was also high, with correlation coefficients ranging from $R(k=i) = 0.823$ to 0.977 .

High correlations were also observed between Phase II inter-trial changes in average TT speed and relative W_{Max} ($r = 0.70$ to 0.94). Correlations between inter-trial changes in average TT speed and TTE were generally lower and more variable ($r = 0.26$ to 0.87). These results suggest that changes in relative SDP W_{max} can reliably, validly, and practically track changes in uphill TT performance.

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Owen Frederic Murphy

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. Deborah King

(Signature)

11/19/01
Date

Approved for the Department of Health and Human Development

Dr. Ellen Kreighbaum

(Signature)

11/19/01
Date

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod

(Signature)

11-29-01
Date

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Date NOVEMBER 19, 2001

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ABSTRACT

The ability to accurately quantify and predict endurance performance is imperative when assessing the effects of training interventions, dietary regimes, equipment modifications, and/or alterations in athlete position or technique. Due to the invasive nature and excessive costs of traditional physiological and biomechanical determinants of endurance performance, performance-based determinants of performance have received considerable attention.

The purpose of the present study was to determine the reliability and validity of a scaling-derived cycle ergometer protocol (SDP) for tracking changes in uphill time-trial (TT) cycling performance. Phase I of the study assessed the reliability of the Scaling Derived Protocol (SDP) via the administration of three SDP protocols within a ten-day time period. Phase II of the study determined the ability of the SDP to track longitudinal changes in uphill time-trial performance. Local competitive cyclists participated in either two or three testing periods separated by a minimum of ten weeks (May, July, September 2001). Each testing period consisted of an outdoor uphill TT (5-km, 8% grade) followed within ten days by a laboratory-based SDP. Longitudinal inter-trial changes in average TT speed (m/s) were compared with longitudinal inter-trial changes in SDP time-to-exhaustion (TTE, min) and relative SDP maximal power output (W_{MAX} , $\text{watts}\cdot\text{kg}^{-1}$).

There were no significant Phase I inter-trial differences for time-to-exhaustion, maximum power output, maximum heart rate, and relative VO_{2MAX} . Intraclass correlation coefficients were high for all variables, ranging from $R = 0.933$ to 0.992 . Single-score reliability was also high, with correlation coefficients ranging from $R_{(k=1)} = 0.823$ to 0.977 .

High correlations were also observed between Phase II inter-trial changes in average TT speed and relative W_{MAX} ($r = 0.70$ to 0.94). Correlations between inter-trial changes in average TT speed and TTE were generally lower and more variable ($r = 0.26$ to 0.87). These results suggest that changes in relative SDP W_{MAX} can reliably, validly, and practically track changes in uphill TT performance.

CHAPTER ONE

INTRODUCTION

The year 2000 saw the rise to dominance some of the world's greatest cyclists. Johan Museeuw celebrated his third victory at Paris-Roubaix, soloing the last 40-km in a stunning display of brute strength and courage. Lance Armstrong won his second consecutive Tour de France, dominating the high-mountain stages and individual time-trials. Leontien Zijlaard was the revelation of the Sidney Olympic Games, winning an unprecedented three gold medals in women's road and track cycling events. Finally, Miguel Martinez became the first mountain biker in history to achieve the overall World Cup, Olympic gold, and the World Championships in the same year.

Such incredible performances (time and time again) beg the question: What sets these champions apart? Are they gifted with extraordinary lung capacities, lactate thresholds, or blood hematocrits? Do they possess the ideal strength-to-weight ratio? Have they developed superior technique or economy of movement? Do they command a greater strength of mind, will to suffer, or desire to win?

In truth, all of these factors contribute to successful endurance performance – cycling or other. Sport scientists today, however, are searching for a *single, easily quantifiable* determinant of performance that could be used to identify, track, and train the best endurance athletes in the world. More importantly, perhaps, coaches at the grassroots level are in need of a practical and affordable method with which to identify

youth talent in a variety of endurance-based sports. Only then will it be possible to nurture the youths of today into the champions of tomorrow.

Historical Background

In 1923, Hill and Lupton were the first sport scientists to note that the world's best endurance athletes also happened to possess the world's highest $\dot{V}O_{2\text{MAX}}$ values when expressed relative to their body mass. It was subsequently proposed (and widely accepted) that relative $\dot{V}O_{2\text{MAX}}$ could be used as a primary determinant of endurance performance (Astrand and Rodahl, 1986; Costill, 1967; Foster, 1978; Hagberg and Coyle, 1983; Saltin and Astrand, 1967). More recently, physiologists have also proposed blood lactate transition thresholds (Farrell et al., 1979; Kumagai et al., 1982; Powers et al., 1983; Yoshida et al., 1987) and economy of movement (Basset and Howley, 2000; Costill and Winrow, 1970; Daniels, 1974; Dengel et al., 1989) as viable determinants of endurance performance.

Despite their strong association with successful endurance performance, however, physiological determinants ($\dot{V}O_{2\text{MAX}}$, lactate threshold, and economy of movement) are inherently expensive, invasive, and unavailable to the general public. "Indeed, few coaches and athletes have the ready access to laboratory facilities capable of measuring $\dot{V}O_{2\text{MAX}}$, as such a test requires expensive equipment, skilled personnel, and is time-consuming" (Hawley and Noakes, 1992, pp. 79). Given these drawbacks, physiological determinants of endurance performance are rendered impractical means with which to screen youth talent and/or repeatedly monitor an endurance athlete's progress.

Fortunately, several contemporary cycling-related studies have indicated the importance of average or peak muscular power as a valid and relatively affordable determinant of endurance performance. In such investigations, power-measuring devices (e.g. Computrainer™, SRM™, Tune Power Tap™) are used to measure a cyclist's power output in watts. The results have been stunning. For instance, Palmer et al. (1996), observed a correlation of $r = -0.999$ between average power output and both 20-km and 40-km cycling time-trial performance! Bishop et al. (1998) and Coyle et al. (1991) reported correlations of $r = -0.81$ and $r = -0.88$, respectively, between average power output and actual 40-km time-trial performance. In a study of sub-elite male cyclists, Balmer et al. (2000) found a correlation of $r = -0.99$ ($p < 0.001$) between peak power output (PPO) and 16.1-km time-trial performance. Lastly, Bishop et al. (1998), Lindsay et al. (1996), and Schabort et al. (2000) observed high correlations ($r = -0.81$ to -0.91) between PPO and 20-km to 40-km cycling time-trial performance.

In an effort to improve upon the validity, reliability, and theoretical foundation of PPO protocols, Heil et al. (2000) introduced a scaling derived protocol (SDP) based on the energy requirements of uphill cycling as influenced by body mass. Preliminary results indicate that SDP performance (time-to-exhaustion) correlates extremely well with actual uphill time-trial performance ($r = 0.97$ to 0.98), as does relative SDP peak power output ($\text{watts} \cdot \text{kg}^{-1}$; $r = 0.92$ to 0.97). The SDP is easy to administer and completely objective because gravity affects all cyclists in the same manner, regardless of age, gender, or technique. In addition, the design of the SDP allows it to serve as a $\dot{V} \text{O}_{2\text{MAX}}$ test for cyclists when appropriate.

Given the impressive correlations between SDP performance and uphill time-trial performance, the current investigation was undertaken to determine the ability of the SDP to track *changes* in uphill time-trial performance. Though such ability may seem a rather simple and straightforward proficiency, the author knows of no existing protocol so apt.

Statement of Purpose

The primary purpose of this study was to determine the ability of the Scaling Derived Protocol (SDP) to validly track changes in uphill cycling time-trial performance. A secondary purpose of this study was to assess the test-retest reliability of the SDP.

Significance of Study

The results from this study will be of value to cyclists, coaches, and sport scientists as they attempt assess the effects of various training interventions, dietary regimes, equipment modifications, and/or alterations in athlete position and technique. This should ultimately lead to more effective cycling training. The portability, affordability, and practicality of the SDP also bodes well for local youth talent identification programs for cycling. Additionally, the potential exists to extend the principles of the SDP to other endurance-based sports such as running and cross-country skiing.

Hypotheses

1. Phase I: The Scaling Derived Protocol (SDP) is a reliable measure of cycling performance. Intraclass correlation coefficients (ICC) were assessed via the administration of three SDP protocols to local cyclists within a 10-day period.

$$H_0: ICC < 0.80$$

$$H_a: ICC \geq 0.80$$

2. Phase II: The Scaling Derived Protocol (SDP) is a valid means of tracking changes in uphill cycling time-trial performance (TT).

$$H_0: \rho = 0 \text{ (No correlation exists between changes in SDP performance and changes in TT performance)}$$

$$H_a: \rho \neq 0 \text{ (Correlation exists between changes in SDP performance and TT performance)}$$

Limitations

- 1) Phase II: The time-trial course was three miles long and featured a 500-meter section of level grade approximately two-thirds of the way to the finish.

Considering the available course options in the Bozeman area, however, the chosen venue was the most suitable to the purposes of this study.
- 2) Phase II: Weather conditions (namely wind and air temperature) varied between each of the three uphill time trials (May, July, and, September 2001).
- 3) Phase II: Weight categories (and consequent SDP resistance levels) were fixed for the entire study period, regardless of fluctuations in subjects' weight.

Delimitations

- 1) Phase I/II: The scope of this study was delimited to competitive and recreational cyclists in the Bozeman, Montana area.
- 2) Phase II: Due to health-related contraindications to maximal intensity exercise, this study was delimited to "low and moderate risk individuals" (as defined by ACSM's Guidelines for Exercise Testing and Prescription, 6th ed., 2000). In the current study, "moderate risk individuals" refers to several male subjects over the age of 45 years.

Operational Definitions

Cadence:	The rate of pedaling, measured in revolutions per minute of one foot, e.g. pedal frequency or pedaling rate (Borysewicz, 1985).
Change-score:	An index of Phase II inter-trial change calculated by subtracting the performance score of one trial (pre) from that of another (post); the absolute difference between trials.
Computrainer TM :	A commercially available stationary trainer that allows the application of variable resistance (in watts) to the rear wheel of a bicycle.
Economy of Movement:	The oxygen cost of exercising at a standard, submaximal velocity or power output.
Endurance Performance:	The ability to maintain a relatively high intensity of exercise (>80% max) for extended periods of time (>1 hour).
Lactate Threshold:	The balance point between lactate entry and removal from the blood.
Maximal Oxygen Consumption:	The highest rate at which ambient oxygen can be taken up and utilized by the body during maximal intensity exercise.
Power Output:	Watts produced per kilogram of body mass on a cycle ergometer; measured at the crank, rear hub, or tire/trainer interface.
Singe-Score Reliability:	The reliability of a performance protocol given only one test administration.
Time-Trial:	A race against the clock in which individual riders start at set intervals and cannot give aid or receive it from others on the course.

CHAPTER TWO

REVIEW OF LITERATURE

Introduction

The ability to accurately quantify and predict endurance performance has become an increasingly important focus in recent decades. Ever since Hill and Lupton (1923) demonstrated a positive correlation between maximal oxygen uptake ($\dot{V}O_{2\text{MAX}}$) and middle-distance running performance, researchers have sought to identify additional physiological and biomechanical factors associated with success in endurance events. Commonly referred to as “determinants of endurance performance”, these factors are used to evaluate the effects of training strategies (Hickson et al., 1988; Lindsay et al., 1996; Westgarth-Taylor et al., 1997; Weston, et al., 1997), nutritional interventions (Coggan and Coyle, 1987; El-Sayed et al., 1997; Palmer et al., 1998), alterations in body position or bicycle geometry (Heil, 1997; Heil et al., 1997; Heil et al., 1995), and equipment changes (MacRae et al., 2000), as well as predict the performance capacity of endurance athletes (Balmer et al., 2000; Hawley and Noakes, 1992; Heil et al., 2000; Kuipers et al., 1985; Miller and Manfredi, 1987).

However, due to the inability of a single physiological or biomechanical factor to determine and/or predict endurance performance in homogeneous populations, a number of researchers have proposed the use of performance-based laboratory protocols. This review will examine the most common physiological and performance-based

determinants of endurance performance, with particular respect to the validity and/or practicality of each. Other factors related to endurance performance, such as biomechanics, psychological preparation, and nutritional status will not be discussed.

Physiological Determinants of Endurance Performance

Maximal oxygen consumption ($\dot{V}O_{2MAX}$) has traditionally been used as *the* criterion measure of endurance performance (Astrand and Rodahl, 1986; Bassett and Howley, 2000; Costill, 1967; Coyle et al., 1988; Craig, et al., 1993; Foster, 1978; Hagberg and Coyle, 1983; Hill and Lupton, 1923; Noakes, 1988; Saltin and Astrand, 1967; Sleivert and Rowlands, 1996). However, several investigators have recently suggested that physiological parameters measured during submaximal exercise may provide better predictors of endurance performance than $\dot{V}O_{2MAX}$. These parameters include blood lactate transition thresholds (Barlow et al., 1985; Coyle, et al., 1991; Craig, et al., 1993; Farrell, et al. 1979; Hagberg and Coyle, 1983; Hopkins and McKenzie, 1994; Jacobs, 1986; Loftin and Warren, 1994; Miller and Manfredi, 1987; Powers et al., 1983; Schabort et al., 2000; Sjodin, 1981; Yoshida et al., 1987) and economy of movement (Conley and Krahenbahl, 1980; Costill et al., 1985; Powers et al., 1983; Schabort et al., 2000).

Maximal Oxygen Uptake

Maximal oxygen uptake ($\dot{V}O_{2MAX}$) is considered a primary determinant of endurance performance, generally because it sets the upper limit for steady-state oxygen

consumption (Astrand and Rodahl, 1986; Costill, 1967; Craig, et al., 1993; Evans et al., 1995; Foster, 1978; Hill and Lupton, 1923). It is defined as the highest rate at which ambient oxygen can be taken up and utilized by the body during maximal intensity exercise. Provided the absence of pulmonary disease, $\dot{V}O_{2MAX}$ is the best indicator of an individual's cardiovascular fitness level (Brooks et al, 1996).

Support for the use of $\dot{V}O_{2MAX}$ as a determinant of endurance performance is based on the fact that most endurance athletes have relatively high $\dot{V}O_{2MAX}$ values (Costill et al., 1973; Coyle, et al., 1988, 1991; Saltin and Astrand, 1967; Sleivert and Rowlands, 1996), and relatively strong correlations have been reported between $\dot{V}O_{2MAX}$ and endurance performance (Costill, 1967; Farrell et al., 1979; Foster et al., 1978; Sleivert and Rowlands, 1996). In contrast, a number of researchers have found that $\dot{V}O_{2MAX}$ is inadequate at predicting endurance performance within a homogeneous group of well-trained endurance athletes (Conley and Krahenbuhl, 1980; Coyle et al., 1988; Hagberg et al., 1979; Lindsey et al., 1996). "This [paradox] seems to indicate that a high $\dot{V}O_{2MAX}$ capacity is necessary to compete in endurance events, but $\dot{V}O_{2MAX}$ alone cannot be used to discriminate between highly trained endurance athletes of similar $\dot{V}O_{2MAX}$ " (Barlow et al., 1985, pp. 194). In such cases, lactate threshold, economy, and/or performance during specific laboratory protocols have proven better indicators of endurance performance than $\dot{V}O_{2MAX}$ (Allen et al., 1985; Bishop et al, 1998; Conconi et al., 1982; Conley and Krahenbuhl, 1980; Craig et al., 1993; Farrell et al., 1979; Heil et al., 2000; Weltman et al., 1990).

Lactate Threshold

Lactate threshold (LT) and/or anaerobic threshold is defined as the balance point between lactate entry and removal from the blood. It is often represented by an athlete's $\dot{V}O_2$ (ml/kg/min) at LT, or their corresponding power output on a cycle ergometer (e.g. 300 watts). The use of LT as a determinant of endurance performance is supported by the following observations: 1) during endurance competition most athletes perform at some percentage of their $\dot{V}O_{2MAX}$ rather than at their absolute maximum (Costill and Fox, 1969; Coyle et al., 1988; Farrell et al., 1979); 2) athletes with a relatively higher LT exhibit superior endurance performance (Coyle et al., 1988; Farrell et al., 1979; Schabort et al., 2000; Sjodin and Jacobs, 1982); 3) a delayed LT should result in decreased glycogen depletion and increased time-to-exhaustion since elevated lactate levels are associated with increased glycogen utilization (a recognized limitation to endurance performance), (Costill et al., 1971a, 1971b; Coyle, 1988). Moreover, in studies that have correlated LT and $\dot{V}O_{2MAX}$ with endurance performance, LT has been more strongly related, both in trained subjects (Farrell et al., 1979; Kumagai et al., 1982; Powers et al., 1983) and untrained subjects (Yoshida et al., 1987).

However, the concept and application of lactate and/or anaerobic thresholds are the targets of considerable debate. Despite 60 years of blood lactate research, there is still a great deal of controversy surrounding the explanation of lactate and/or anaerobic thresholds and the methods used to identify them. In fact, points of contention probably outnumber points of agreement (Bourdon, 2000).

The principal point of contention involves the method by which blood lactate transition thresholds are defined – fixed blood lactate concentrations or individualized lactate thresholds. Fixed blood lactate concentrations ranging from 2 to 4 mmol/L have been used by a number of investigators in order to minimize problems associated with detecting inflections in the blood lactate response curve (Allen et al, 1985; Hagberg et al, 1986; Heck et al., 1985; Kindermann et al., 1979; Sjodin, 1983). However, fixed blood lactate concentrations may be influenced by an individual's nutritional and training status. For example, $\dot{V}O_2$ obtained at the onset of blood lactate accumulation was significantly lower after a high carbohydrate diet than after a low carbohydrate diet (Yoshida, 1984).

Stegmann et al. (1981) reported that steady state blood lactate concentrations can vary widely among athletes, thus lending additional support to the use of individualized lactate thresholds. However, the detection of inflection points in individualized blood lactate curves is a complicated and controversial matter in and of its own. Several interpretational methods exist, including log-log transformations (Beaver, et al, 1985), rates of metabolite accumulation (Thoden, 1991), tangential techniques (Cheng et al., 1992), and subjective visual inspections (Yoshida et al., 1985), but none has proven overly superior.

A second major point of contention surrounding the concept of "lactate threshold" addresses the protocol(s) used to elicit blood lactate responses, collect blood samples, and analyze lactate concentrations. "Protocol-related factors such as the sampling site, workload duration, continuous versus discontinuous exercise bouts, and choice of

ergometer can all affect the measurement of blood lactate response to incremental exercise" (Bourdon, 2000, pp. 56). The longer the workload duration, for instance, the lower the LT (Heck et al., 1985; McLellan 1987). In contrast, the longer the rest breaks during a discontinuous protocol, the higher the LT (Heck et al., 1985; Foster et al., 1995). A complete summary of the exercise protocols and sampling/analysis methods used to evaluate blood lactate concentrations is beyond the scope of this paper, but suffice it to say that a significant number of procedural, physiological, and environmental factors exist with the potential to alter the blood lactate-exercise intensity relationship.

Economy of Movement

There is a distinct linear relationship between submaximal power output and $\dot{V}O_2$ for each individual. However, considerable variation exists in just how much oxygen is required to exercise at a given intensity or power output. Several researchers have proposed this $\dot{V}O_2$ discrepancy can be attributed to inter-individual differences in economy of movement (Basset and Howley, 2000; Costill and Winrow, 1970; Daniels, 1974).

Economy of movement is defined as the oxygen cost (ml/kg/min) of exercising at a standard submaximal velocity or power output (Basset and Howley, 2000; Farrell et al., 1979; Powers et al., 1983; Schabort et al., 2000). Intuitively, better economy results in better performance: a more economical athlete uses less oxygen at a standard velocity and theoretically is able to move faster and/or conserve more energy than a less economical athlete (Sleivert and Rowlands, 1996).

Research concerning the use of economy as a determinant of endurance performance first appeared in the literature during the early 1970s. Costill and Winrow (1970) suggested that variations in the performance of two middle-aged ultramarathon runners with similar $\dot{V}O_{2MAX}$ values could be attributed to individual differences in economy. Several years later, Daniels (1974) reported that economy of movement was responsible for nearly identical 2-mile run times (10:31 and 10:35) among two champion male runners with significantly different $\dot{V}O_{2MAX}$ values (> 10 ml/kg/min). In each case, the more economical runner was able to perform at a lower percentage of his or her relative $\dot{V}O_{2MAX}$, thus decreasing the power of $\dot{V}O_{2MAX}$ to predict overall performance.

Additionally, Conley and Krahenbahl (1980) observed a correlation of $r = 0.82$ between economy of movement and 10-km running performance in a study of highly trained male distance runners with similar $\dot{V}O_{2MAX}$ values. These data were later used by Basset and Howley (1997) to explain how running economy could account for a large portion of the variability in distance running performance. In other sports, Dengel et al. (1989) reported that the strongest predictor of triathlon performance was a combined measure of swimming, cycling, and running economy.

In direct contrast to the above researchers, Farrell et al. (1979) and Powers et al. (1983) reported a significant *lack* of correlation between economy and endurance performance. Working independently, Farrell and Powers reported poor correlations ($r = 0.49$ to 0.59) between running economy and distance running performance in homogeneous well-trained populations. "The failure to show a significant relationship between running economy and running performance... suggests that in some populations

the individual differences in running economy at a standardized speed is not great, and that running economy may be of limited value in differentiating distance running performance" (Powers et al., 1983, pp. 182).

Noakes (1998) is another prominent physiologist hesitant to endorse economy of movement as a primary determinant of endurance performance. In rebuttal to the aforementioned claims presented by Basset and Howley (1997), Noakes cites large discrepancies in their study population – individual performances differed by 18 minutes (38%) in a 16-km race, and by 9 minutes (20%) in a 10-km race! However, "...in studies of athletes whose performances are more similar, neither $\dot{V}O_{2MAX}$ nor economy is a good predictor of running performance" (Noakes, 1998, pp.1392).

Performance-Based Protocols as Determinants of Endurance Performance

The primary purpose of performance-based protocols is to simulate the demands of real world competition in a controlled environment. Ideally, these protocols should be reliable, valid, and sensitive to small changes in an athlete's fitness level. These qualities are especially important when performing repeated measurements over a period of time, or when laboratory data is applied to the field to predict actual performance (Balmer, Davison, and Bird, 2000).

Traditional performance-based endurance protocols include time-to-exhaustion at a fixed workload or percentage of $\dot{V}O_{2MAX}$ (Acevedo and Goldfarb, 1989; Billat et al., 1988; Burnham et al., 1995; Coggan and Coyle, 1987; Coyle et al., 1988; Hickson et al., 1988; Jeukendrup et al., 1996; McLellan et al., 1995), time to completion of a fixed

workload or distance (Acevedo and Goldfarb, 1989; Coyle et al., 1991; Farrell et al., 1979; Foster et al., 1993; Hickey et al., 1992; Jeukendrup et al., 1996; Lindsay et al., 1996; Loftin and Warren, 1994; Nichols et al., 1997; Palmer et al., 1995; Schabert et al., 1998; Williams and Cavanagh, 1987), average power output or power output at lactate threshold (Bishop, 1997; Bishop et al., 1998; Coyle et al., 1991; Davison et al., 2000; Hopkins and McKenzie, 1994; Nichols et al., 1997; Palmer et al., 1996; Smith et al., 1999), and peak power achieved during exercise (Balmer et al., 2000; Bishop et al., 1998; Hawley and Noakes, 1992; Lindsay et al., 1996; Morgan et al., 1989; Noakes, 1990; Scott and Houmard, 1994; Schabert et al., 2000).

Time-to-Exhaustion at a Fixed Submaximal Workload

A continuous protocol at a submaximal workload until volitional exhaustion is the classical and most common determinants of endurance performance (Jeukendrup et al., 1996). This type of protocol is usually performed at exercise intensities ranging from 60% to 90% of $\dot{V}O_{2MAX}$, and has reportedly correlated well with endurance performance (Acevedo and Goldfarb, 1989; Billat et al., 1988; Burnham et al., 1995; Coggan and Coyle, 1987; Coyle et al., 1988; Hickson et al., 1988). However, a growing number of researchers have indicated this genre of protocol to be highly variable and unreliable (Jeukendrup et al., 1996; Krebs and Powers, 1989; McLellan et al., 1995).

For example, Krebs and Powers (1989) and McLellan et al. (1995) independently determined coefficients of variation (CV) ranging from 2.8% to 55.9% in untrained subjects cycling to fatigue at 80% $\dot{V}O_{2MAX}$, indicating the irreproducibility of

submaximal tests to exhaustion. Jeukendrup et al. (1996) reported a CV ranging from 17-40% in well-trained cyclists riding to fatigue at approximately 85% $\dot{V}O_{2MAX}$. Additionally, Billat et al (1994) reported a CV of 25% when “sub-elite” subjects were asked to run to exhaustion at their relative lactate threshold.

The poor reproducibility of time-to-exhaustion (TTE) protocols is widely attributed to psychological factors. “Because [TTE] tests have an ‘open end’, psychological factors that might influence performance, such as motivation, monotony, and boredom, are more pronounced than in the time trial oriented approach where the ‘endpoint is known’” (Jeukendrup et al., 1996, p. 269). TTE protocols are further criticized because they are time-consuming and fail to mimic normal competitive situations (Schabert et al., 1996).

Time to Completion of a Fixed Workload or Distance

In comparison to TTE protocols, endurance performance protocols in which athletes are asked to complete a fixed amount of work or distance in the shortest possible time are more reliable (Bishop, 1997; Hickey et al., 1992; Jeukendrup et al., 1996; Palmer et al., 1995; Schabert et al., 1996). Palmer et al. (1995) and Hickey et al. (1992), determined a CV ranging from only 1.0% to 3.1% for cyclists performing 20 to 40-km and 5 to 40-mile time-trials, respectively. Similarly, Bishop (1997) and Jeukendrup et al. (1996) determined a CV of 2.7% and 3.4%, respectively, when subjects were asked to complete as much work as possible in 60 minutes of cycling.

As well as being reliable, protocols of fixed duration or workload have also correlated well with actual endurance performance (Coyle et al., 1991; Palmer et al., 1992). In a study of elite male cyclists, Coyle et al. (1991) reported a correlation of $r = 0.93$ between time to completion of a 40-km laboratory time-trial and actual 40-km time-trial performance. Likewise, Palmer et al. (1995) reported a correlation of $r = 0.98$ between 20-km and 40-km laboratory time-trials and actual road racing performance.

Similar to TTE protocols, however, fixed duration/workload protocols are inherently time-consuming. For example, a 40-km time-trial may take up to 1.5 hours to complete for a sub-elite cyclist. This fact alone renders fixed duration/workload protocols impractical for situations that necessitate the testing of multiple subjects. Also, due to their time-consuming nature, prolonged fixed duration/workload protocols suffer the same negative psychological factors that affect TTE protocols (Hickey et al., 1992).

Measures of Power

Of all the existing determinants of endurance performance, none have proven so overwhelmingly reliable and valid as measures of power output (watts kg^{-1}). Power is, in essence, a manifestation of all possible physiological and biomechanical determinants of endurance performance. By definition, power is the capacity to perform a given amount of work in the shortest possible amount of time. Although power-measuring devices used to be relatively expensive, recent advances in technology have made the quantification of power (in watts, W) much more feasible for coaches and athletes alike.

It is important to note the existence of two different methods of quantifying power output: 1) average power output and 2) peak power output. The first studies to explore the relationship between power and endurance performance relied on measures of average power output (Bishop et al., 1998; Coyle et al., 1991; Davison et al., 2000; Hopkins and McKenzie, 1994; Nichols et al., 1997; Palmer et al., 1996; Smith et al., 1999). Incredibly, Palmer et al. (1996) observed a near perfect correlation ($r = -0.999$, $p < 0.001$) between average power output and both 20-km and 40-km cycling time-trial performance. Bishop et al. (1998) and Coyle et al. (1991) reported correlations of $r = -0.81$ and $r = -0.88$, respectively, between average power output during a one-hour laboratory time-trial and actual 40-km time-trial performance among experienced male and female cyclists and triathletes. Finally, Nichols et al. (1997) and Smith et al. (1999) independently reported correlations of $r = -0.77$ to -0.91 between power output at LT and 13.5-km to 20-km cycling time-trial performance.

More recent studies of power have involved the measurement of peak power output (PPO) (Balmer et al., 2000; Bishop et al., 1998; Hawley and Noakes, 1992; Heil et al., 2000; Lindsay et al., 1996; Morgan et al., 1989; Noakes, 1990; Scott and Houmard, 1994; Schabert et al., 2000). In a study of sub-elite male cyclists, Balmer et al. (2000) reported a correlation of $r = -0.99$ ($p < 0.001$) between PPO and 16.1-km time-trial performance. Bishop et al. (1998), Lindsay et al. (1996), and Schabert et al. (2000) also observed high correlations ($r = -0.81$ to -0.91) between PPO and 20-km to 40-km cycling time-trial performance. In runners, the peak treadmill velocity achieved during an incremental test to exhaustion (a reciprocal measure of PPO) has proven to be a strong

indicator of endurance performance as well (Morgan et al., 1989; Noakes, 1990; Scott and Houmard, 1994).

A new PPO protocol has been proposed by Heil et al. (2000). Based on the external power demand (W_D , W) of steep uphill cycling, Heil and coworkers developed a scaling derived cycling protocol (SDP) that correlates extremely well with actual uphill cycling time-trial performance ($r = 0.97$ to 0.98). The SDP "...utilizes findings from both correlational and body mass scaling studies in cycling to derive an ergometer test protocol that [can] accurately predict uphill cycling time-trial performance" (Heil et al., 2000, p. 3).

In general, W_D for outdoor cycling is considered to be the vector sum of rolling resistance (R_R), aerodynamic drag (R_D), and gravitational resistance (R_G) (Bassett et al., 1999, di Prampero et al., 1979, Olds et al., 1995). During steep uphill cycling, however, R_R and R_D are considered negligible and R_G is the primary resistance ($W_D \propto R_G$). As such, the SDP is completely objective (gravity affects all cyclists in the same manner, regardless of age, gender, or technique). The SDP is also easy to administer, practical, and cost-effective (necessary equipment $< \$1000$) for coaches and athletes outside the sports science laboratory environment. In addition, the design of the SDP as an incremental test to volitional exhaustion makes it possible for the SDP to serve as a $\dot{V}O_{2MAX}$ test for cyclists when appropriate.

Summary

Average and peak power output are the most valid determinants of endurance cycling performance. Consequently, the need to measure physiological variables such as $\dot{V}O_{2\text{MAX}}$, LT, and economy of movement is questionable: few coaches and athletes have the ready access to laboratory facilities capable of measuring $\dot{V}O_{2\text{MAX}}$, or the finances. Additionally, the affordability and availability of power-measuring devices has made performance protocols like the SDP increasingly attractive.

The SDP is a relatively new laboratory cycling protocol based the external power demand of steep uphill cycling. The SDP is a practical and cost-effective measure of peak power output and, therefore, uphill cycling time-trial performance. SDP time-to-exhaustion ($r = 0.97$ to 0.98) and W_{MAX} (watts per kilogram, $r = 0.92$ to 0.97) are highly correlated with actual uphill time trial performance, indicating that a laboratory protocol of relatively short duration (10-12 minutes) can predict exercise performance of much longer duration (15-60 minutes). Therefore, the SDP may serve as an effective marker for tracking changes in actual time-trial performance.

CHAPTER THREE

METHODOLOGY

Introduction

This investigation was conducted in two phases. Phase I of the study assessed the reliability of the Scaling Derived Protocol (SDP); Phase II of the study determined the ability of the SDP to track changes in uphill time-trial performance. In this chapter, the subject characteristics, data collection techniques, and required instrumentation are presented. Included in this chapter is a brief review of the rationale behind the SDP. Finally, the statistical procedures for the stated hypotheses of this study are documented.

The subjects recruited for both phases of the study consisted of a heterogeneous mix of male and female cyclists of varying age, athletic ability, and cycling experience. All subjects were informed of the nature of the investigation and written consent was obtained in accordance with the guidelines set forth by the Montana State University Human Subjects Committee (see Appendix A). Subjects were instructed to prepare for each of the laboratory and field tests as they would for a true competition. Subjects used their own racing bicycle mounted on a commercially available stationary trainer (Computrainer™ Pro, Model 8001, Racermate Inc., Seattle WA., USA) for all laboratory-based SDP tests.

Phase ISubjects

Twenty-three cyclists from Montana State University and the local Bozeman community volunteered participation for Phase I of the study. Two subjects resigned due to general fatigue and acute knee pain, respectively. Physical characteristics and cycling experience of the remaining subjects ($n = 21$) are presented in Table 1.

Table 1. Subject Characteristics, Phase I ($n=21$). Repeated measures reported as Mean $\pm$ SD.

Subject ID#	Gender	Age (yrs)	Body Mass (kg)	Height (m)	Competition Level*
1	F	29	59.3 (0.6)	1.66	2
2	F	27	50.8 (0.4)	1.57	2
3	F	23	71.5 (1.0)	1.73	2
4	F	21	59.3 (0.2)	1.63	3
5	F	27	62.0 (0.5)	1.65	2
6	M	21	66.8 (0.3)	1.78	1
7	M	26	81.5 (0.8)	1.84	3
8	M	25	79.5 (1.0)	1.87	2
9	M	36	80.5 (1.8)	1.85	1
10	M	21	71.3 (0.3)	1.77	1
11	M	24	86.8 (0.1)	1.72	3
12	M	24	71.8 (0.5)	1.76	3
13	M	28	77.3 (0.5)	1.82	2
14	M	21	84.0 (0.0)	1.85	3
15	M	26	71.3 (0.7)	1.74	1
16	M	33	78.0 (0.2)	1.88	1
17	M	20	76.8 (0.1)	1.80	2
18	M	29	80.0 (1.0)	1.89	1
19	M	31	80.0 (0.6)	1.85	2
20	M	34	80.0 (0.6)	1.87	1
21	M	21	77.8 (0.2)	1.87	1
Ave (SD)		26 (4.7)	73.6 (9.3)	1.78 (0.09)	

*Competition Level is reflective of the classification systems used by the United States Cycling Federation (USCF) and the National Collegiate Cycling Association (NCCA): 1 = USCF Category 1-2 and/or NCCA Category A; 2 = USCF Category 3 and/or NCCA Category B; 3 = USCF Category 4 and/or NCCA C-D.

Scaling Derived Protocol

Upon arrival at the laboratory, bicycle rear tire pressure was standardized at 100 p.s.i. using a track pump with tire gauge (Specialized, USA). Each subject's bicycle was fitted to a Computrainer™ stationary trainer (Computrainer™ Pro, Model 8001, Racermate Inc., Seattle WA., USA) and calibrated according to the manufacturer's recommended procedure (see Instrumentation, Pg. 29, for a complete description of the calibration process). Subject age was recorded to the nearest year, subject height (barefoot) was measured to the nearest centimeter, and subject mass (with cycling clothes, minus shoes) was measured to the nearest 0.25 kilogram. When anthropometric measurements were complete, subjects were permitted a subjectively adequate warm-up period (10-30 minutes).

The power output (in watts, W) for each stage of the SDP was based on research previously conducted in this laboratory. In brief review, Heil (1998) determined that the external power demand (W_D) of uphill cycling scales with body mass (M_B) to the +0.89 power (e.g. $W_D \propto M_B^{0.89}$). Thus, the relative energetic cost of uphill cycling at a given speed and grade is less for heavier cyclists than for lighter cyclists. Assuming that the net external power demand of uphill cycling is equivalent to a cyclist's metabolic power supply (Heil, 1998), Heil et al. (2000) modified the standard formula for power (Power = [average acceleration * mass] * average speed) to reflect the scaling relationship between body mass and uphill power demand:

$$\text{Power} = [g * M_B^{0.89} * \sin\theta] * s$$

where “g” is the constant of gravitational acceleration (9.81 m/s/s), “ θ ” is the average inclination angle of the road surface, and “s” is the average forward ground speed of the cyclist.

Using this equation, the power required for each cyclist to ride up a 5° slope (θ) at 6.72 m/s (s) was calculated and designated as Stage 5 of the SDP. Stage 1 of the SDP was then calculated as 20% of the Stage 5 power output value, Stage 2 as 40%, Stage 3 as 60%, Stage 4 as 80%, Stage 5 as 100%, and each stage thereafter increased by 10% (see Appendix B for a complete outline of the first 14 stages for subjects weighing 40-100 kg). Due to wattage limitations imposed by the Computrainer™, it was necessary to approximate SDP power output to the nearest ± 10 W. End measures of the SDP included time-to-exhaustion (TTE, min), maximum power output (W_{MAX} , W/kg), and maximum oxygen uptake ($\dot{V}O_{2MAX}$, ml/kg/min).

SDP Subject Procedure

The subjects were allowed to select their own pedal cadence throughout the first five stages of the protocol, with the stipulation that their chosen pedal cadence be held constant (± 2 rpm) within a given stage. When the subjects reached Stage 6, however, the investigator fixed the cadence for the remainder of the test based upon the observed cadence at that moment. The subjects remained seated during the entire protocol and were verbally encouraged to continue until volitional exhaustion, or until the investigator noted a drop in cadence of ≥ 5 RPM for ≥ 5 seconds. Time to completion (e.g. time-to-exhaustion) of the SDP test was recorded to the nearest second.

Maximal power output (W_{MAX}) and maximal oxygen uptake ($\dot{V}O_{2MAX}$) were also determined during the SDP test. W_{MAX} was defined as the power output corresponding to the final completed stage of the SDP, plus a fraction of the power output maintained in the final incomplete stage (Kuipers et al., 1985):

$$W_{MAX} = (W_{com} + t/60) * \Delta W$$

where W_{com} is the power output of the final completed SDP stage, t is the amount of time (sec) completed in the final uncompleted stage, and ΔW is the power output of the final incomplete stage. Maximum oxygen consumption was calculated as the average of the three highest consecutive $\dot{V}O_2$ measures during the SDP. The measurement of $\dot{V}O_{2MAX}$ was considered successful if two of the following three criteria were met: 1) A maximal heart rate within 10 beats of each subject's age predicted maximum heart rate (e.g. 220-age); 2) A maximum respiratory exchange ratio of ≥ 1.10 before the last successful $\dot{V}O_2$ measurement; 3) A plateau of $\dot{V}O_2$ evidenced by a change ≤ 2.1 ml/kg/min with an increase in power output.

In order to determine the test-retest reliability of the SDP, each subject performed three maximal SDP tests within a ten-day period. The tests were conducted at the same time of day and separated by a minimum of 48 hours. Subjects were asked to maintain their normal diet and training load throughout the 10-day testing period.

Phase IISubjects

Eighteen cyclists from Montana State University and the local Bozeman community volunteered participation for Phase II of the study. Three subjects resigned due to schedule conflicts or lack of motivation; two more cyclists moved away from the area prior to completion of the study. Physical characteristics and cycling experience of the remaining subjects ($n = 13$) are presented in Table 2. In order to determine the ability of the SDP to predict and track uphill time-trial performance over time, each subject participated in at least two of three matched field and laboratory tests.

Table 2. Subject Characteristics, Phase II ($n=13$). Repeated measures reported as Mean $\pm$ SD.

Subject ID#	Trials Completed	Gender	Age (yrs)	Body Mass (kg)	Height (m)	Competition Level*
1	1,2,3	F	29	56.3 (0.9)	1.60	2
2	1,2	F	27	54.3 (0.4)	1.63	2
3	1,2,3	M	29	74.5 (1.9)	1.65	2
4	1,2,3	M	29	69.0 (1.0)	1.75	1
5	1,3	M	24	70.3 (1.8)	1.76	3
6	1,2,3	M	48	77.0 (0.1)	1.78	3
7	1,2	M	29	80.0 (0.7)	1.89	1
8	1,2	M	37	83.3 (2.1)	1.78	1
9	1,2,3	M	44	81.8 (0.6)	1.85	1
10	1,2,3	M	24	81.0 (2.8)	1.78	3
11	1,3	M	33	78.8 (0.5)	1.88	1
12	1,2,3	M	53	73.8 (0.9)	1.78	1
13	2,3	M	36	81.0 (0.7)	1.88	1
Ave (SD)			34 (9.2)	73.8 (9.3)	1.77 (0.09)	

*Competition Level is reflective of the classification systems used by the United States Cycling Federation (USCF) and the National Collegiate Cycling Association (NCCA): 1 = USCF Category 1-2 and/or NCCA Category A; 2 = USCF Category 3 and/or NCCA Category B; 3 = USCF Category 4 and/or NCCA C-D.

Field Testing

The uphill time-trial course was located at the entrance to the Lewis and Clark Caverns State Park, approximately 50 miles west of Bozeman (Figure 1). The course was five kilometers long, with an average gradient of 8%. Starting elevation was 1301 meters (4,270 feet) above sea level, and ending (maximum) elevation was 1618 meters (5307 feet) above sea level (Figure 2). The course was fairly sheltered from wind for the first 3.5 kilometers, but became more exposed towards the finish. The course leveled off for 500 meters at kilometer 3, but then climbed again to the finish. Subjects were provided with a standing start (bicycle and rider supported by the primary investigator). A minimum of four digital handheld stopwatches were synchronized prior to each time-trial; two stopwatches were transported to the top of the course to record finishing time and two stopwatches remained at the bottom for starting purposes. Time-trial performance was recorded to the nearest second. Average time-trial speed was calculated by dividing the performance time by the total time-trial distance (5.0 km). Each uphill time-trial was separated by exactly ten weeks (May 10th, July 19th, September 27th, 2001).

Laboratory Testing

Each uphill time-trial was followed within ten days by a laboratory-based SDP. A minimum of 48 hours separated the field and laboratory tests. The SDP protocol was performed in the same manner as described in Phase I of the investigation. Absolute power output (W , W_{MAX}) was also expressed relative to body mass (W_{MAX}/m_b) and combined subject/equipment mass (W_{MAX}/m_c).

Figure 1. Topographical view of the uphill time-trial course (Lewis and Clark Caverns State Park, MT).

Figure 2. Uphill time-trial course profile.

Instrumentation

Scaling Derived Protocol

For the laboratory-based SDP, each subject's bicycle was fitted to a Computrainer™ stationary trainer (Computrainer™ Pro, Model 8001, Racermate Inc., Seattle WA., USA) that supported the mass of the bicycle and rider at the rear wheel axle. A commercially available plastic riser was placed under the front wheel to level the bicycle. An adjustable roller unit was used to apply resistance to the rear wheel. The resistance applied to the roller unit was, in turn, controlled by an electromagnetic "load generator" via a handlebar-mounted keypad. Real-time measures of power output at the rear wheel, along with pedal cadence recorded by a crank arm sensor, were displayed on the keypad.

The following steps were required to calibrate the Computrainer™ in accordance with the guidelines established by the manufacturer: 1) adjust the trainer stand to fit each bicycle, 2) clean the rear tire of dust and debris, 3) warm-up the rear tire for several minutes, and 4) perform a "roll down calibration". The "roll down" test estimates the rolling resistance between the rear tire and the adjustable roller (which can vary depending on tire pressure, tire temperature, and the amount of pressure between the tire and roller) so that the total resistance applied to the rear wheel is as accurate as possible. The resistance applied to the rear wheel is independent of pedal cadence. The total power output (W) resisted at the rear wheel was controlled by the handlebar-mounted keypad in 10 W increments. The Computrainer™ was calibrated prior to each SDP administration.

Oxygen Consumption

Oxygen consumption for each test was measured by standard open-circuit spirometry using a two-way, low resistance breathing valve. A SensorMedics 2900 metabolic cart (SensorMedics Corporation, Yorba Linda, CA., USA) was employed to continuously monitor expired gases; $\dot{V}O_2$ was calculated over 20-second intervals. Prior to testing, the gas analyzers were calibrated with primary gas standards of known concentrations (26% O_2 , N_2 balance; 4% CO_2 , 16% O_2 , N_2 balance), and the SensorMedics' ventilatory measures were confirmed with a calibrated 3-liter syringe (Model D, SensorMedics Corporation, Yorba Linda, CA., USA). All information was processed via an IBM computer using ProTrac software (Sensor Medics Corporation, Yorba Linda, CA., USA).

Heart Rate

Heart rate data during each test was measured with a Polar Accurex Plus telemetry-based heart rate monitor (Polar Electro Inc., Woodbury, NY., USA). Heart rate was averaged every five seconds and downloaded to an adjacent computer via the serial port interface provided by the manufacturer. Maximal heart rate was determined as the highest five-second average heart rate during the SDP test.

Statistical Analysis

Phase I

SDP reliability was assessed via the calculation of intraclass correlation coefficients (ICC) from corresponding repeated-measures ANOVA: $(ICC) = [(MS_S - MS_W) / MS_S]$, where MS_S is the mean square between subjects and MS_W is the mean square within subjects. According to Vincent (1995), an $ICC > 0.90$ is considered high, an ICC of 0.80 to 0.89 is considered moderate, and an $ICC < 0.80$ is questionable. Single-score reliability ($R_{k=1}$) was calculated to determine the reliability of the SDP given only one test administration: $(R_{k=1}) = [MS_S - MS_W / (MS_S + (K/K' - 1)(MS_W))]$, where K is the number of repeated measures administered and K' is the number of repeated measures for which R is estimated. The standard error of measurement (SEM) and coefficient of variation (CV) were also calculated as additional means of reliability: $SEM = [SD\sqrt{(1-ICC)}]$, where SD is the sample standard deviation; $CV = [SD / \text{sample mean}]$. Repeated-measures ANOVA was performed with StatistixTM computer software (Version 4.0 Analytical Software, St. Paul, MN).

Phase II

Multiple Pearson product-moment correlation coefficients (r) were used to determine the relationship between changes in SDP performance and uphill time-trial performance. Changes were calculated between Trials 1-2, 2-3, 1-3 for all dependent variables. Phase II statistical analyses were performed using StatisticaTM computer software (version 5.5, Statsoft, Inc., Tulsa, OK). The level of significance was preset at $\alpha = 0.05$ for all tests, Phase I and II.

CHAPTER FOUR

RESULTS

Phase I

There were no significant differences between trials for time-to-exhaustion, maximum power output, maximum heart rate, and relative $\dot{V}O_{2MAX}$. Intraclass correlation coefficients were high for all variables, ranging from $R = 0.933$ to 0.992 . Single-score reliability was also high, with correlation coefficients ranging from $R_{(k=1)} = 0.823$ to 0.977 . Reliability data are presented in Table 3.

Table 3. Phase I SDP trial Means $\pm$ SD (range) and reliability data for all subjects ($n = 21$).

	TTE	W_{MAX}	HR_{MAX}	VO_{2MAX}
Trial 1	11.1 $\pm$ 1.3 min (8.4-13.5)	339.6 $\pm$ 56.6 W (231.5-423.5)	190.4 $\pm$ 6.2 bpm (180-202)	63.3 $\pm$ 6.3 ml/kg/min (49.3-75.71)
Trial 2	11.4 $\pm$ 1.1 min (8.8-13.1)	351.5 $\pm$ 48.7 W (237.0-410.0)	189.6 $\pm$ 6.2 bpm (181-202)	63.6 $\pm$ 5.9 ml/kg/min (47.61-72.75)
Trial 3	11.3 $\pm$ 1.2 min (8.8-13.6)	347.3 $\pm$ 51.6 W (238.0-427.5)	189.0 $\pm$ 6.7 bpm (181-204)	63.0 $\pm$ 5.7 ml/kg/min (48.31-72.66)
ICC	0.933	0.967	0.936	0.992
$R_{(k=1)}$	0.823	0.908	0.829	0.977
CV	$\pm 1.49\%$	$\pm 1.74\%$	$\pm 0.36\%$	$\pm 0.48\%$
SEM	± 0.04 min	± 1.09 W	± 0.18 bpm	± 1.53 ml/kg/min

TTE = laboratory protocol time-to-exhaustion; W_{MAX} = maximum power output; HR_{MAX} = maximum heart rate; VO_{2MAX} = relative maximum oxygen consumption; ICC = intraclass correlation coefficient; $R_{(k=1)}$ = single-score reliability; CV = coefficient of variation; SEM = standard error of measurement.

In order to assess potential "learning effects" of prior maximal testing experience on SDP reliability, the primary data set was divided into two subsets (subjects with prior maximal testing experience ($n = 9$) vs. subjects with no prior maximal testing experience ($n = 12$)). There were no significant differences between trials for time-to-exhaustion, maximum power output, maximum heart rate, and relative $\dot{V}O_{2\text{MAX}}$ for subjects with prior maximal testing experience. All variables were reliable with intraclass correlation coefficients ranging from $R = 0.947$ to 0.982 . Single-score reliability was also high, with correlation coefficients ranging from $R_{(k=1)} = 0.826$ to 0.949 . Reliability data for subjects with prior maximal testing experience are presented in Table 4.

Table 4. Phase I SDP trial Means $\pm$ SD (range) and reliability data for subjects with prior maximal testing experience ($n = 9$).

	TTE	W_{MAX}	HR_{MAX}	$VO_{2\text{MAX}}$
Trial 1	10.7 $\pm$ 1.5 min (8.4-13.3)	336.8 $\pm$ 60.0 W (231.5-391.0)	192.1 $\pm$ 6.0 bpm (184-202)	63.0 $\pm$ 6.8 ml/kg/min (50.38-71.33)
Trial 2	11.2 $\pm$ 1.5 min (8.8-13.1)	375.9 $\pm$ 50.0 W (237.0-398.0)	192.4 $\pm$ 6.3 bpm (185-202)	63.5 $\pm$ 5.7 ml/kg/min (54.4-71.3)
Trial 3	11.2 $\pm$ 1.4 min (8.8-12.8)	349.9 $\pm$ 47.6 W (238.0-405.0)	192.3 $\pm$ 7.5 bpm (183-204)	65.6 $\pm$ 5.7 ml/kg/min (53.6-71.5)
ICC	0.947	0.935	0.969	0.982
$R_{(k=1)}$	0.856	0.826	0.913	0.949
CV	$\pm 2.46\%$	$\pm 3.05\%$	$\pm 0.09\%$	$\pm 0.75\%$
SEM	± 0.03 min	± 0.66 W	± 0.03 bpm	± 0.02 ml/kg/min

TTE = laboratory protocol time-to-exhaustion; W_{MAX} = relative maximum power output; HR_{MAX} = maximum heart rate; $VO_{2\text{MAX}}$ = relative maximum oxygen consumption; ICC = intraclass correlation coefficient; $R_{(k=1)}$ = single-score reliability; CV = coefficient of variation; SEM = standard error of measurement.

There were no significant differences between trials for time-to-exhaustion, maximum power output, maximum heart rate, and relative $\dot{V}O_{2\text{MAX}}$ for subjects with no prior maximal testing experience. All variables were reliable with intraclass correlation coefficients ranging from $R = 0.879$ to 0.995 . Single-score reliability was also high with correlation coefficients ranging from $R_{(k=1)} = 0.709$ to 0.986 . Reliability data for subjects with no prior maximal testing experience are presented in Table 5.

Table 5. Phase I SDP trial Means $\pm$ SD (Range) and reliability data for subjects with no prior maximal testing experience ($n = 12$).

	TTE	W_{MAX}	HR_{MAX}	$VO_{2\text{MAX}}$
Trial 1	11.3 $\pm$ 1.0 min (9.5-13.5)	341.7 $\pm$ 56.6 W (245.0-423.5)	189.1 $\pm$ 6.2 bpm (180-198)	63.5 $\pm$ 6.1 ml/kg/min (49.3-75.7)
Trial 2	11.5 $\pm$ 0.8 min (10.0-13.0)	346.7 $\pm$ 49.6 W (270.0-410.0)	187.5 $\pm$ 5.5 bpm (181-198)	63.6 $\pm$ 6.2 ml/kg/min (47.6-72.8)
Trial 3	11.4 $\pm$ 1.0 min (9.7-13.6)	345.4 $\pm$ 56.4 W (245.0-427.0)	186.5 $\pm$ 5.1 bpm (181-195)	63.3 $\pm$ 5.9 ml/kg/min (48.3-72.7)
ICC	0.995	0.991	0.879	0.982
$R_{(k=1)}$	0.986	0.973	0.709	0.947
CV	$\pm 1.0\%$	$\pm 0.8\%$	$\pm 0.9\%$	$\pm 0.3\%$
SEM	± 0.07 min	± 5.37 W	± 2.15 bpm	± 0.10 ml/kg/min

TTE = SDP time-to-exhaustion; W_{MAX} = relative maximum power output; HR_{MAX} = maximum heart rate; $VO_{2\text{MAX}}$ = relative maximum oxygen consumption; ICC = intraclass correlation coefficient; $R_{(k=1)}$ = single-score reliability; CV = coefficient of variation; SEM = standard error of measurement.

Phase II

A minimum of eleven subjects took part in each matched uphill time-trial and laboratory-based SDP (May, July, and September 2001). Relevant performance results are presented in Table 6 (see Appendix C for raw data). Only eight subjects managed to complete all three testing bouts; the remainder of subjects completed two matched testing trials. Table 7 provides a list of relevant environmental conditions encountered during each uphill time-trial.

Table 6. Phase II uphill time-trial and laboratory-based SDP results for all subjects. All values reported as Mean $\pm$ SD (Range).

	Trial 1 (n=12)	Trial 2 (n=11)	Trial 3 (n=11)
1 TT Speed (m/s)	4.5 $\pm$ 0.5 (3.6-5.3)	4.7 $\pm$ 0.5 (3.7-5.6)	4.7 $\pm$ 0.5 (3.6-5.3)
2 SDP TTE (min)	11.3 $\pm$ 1.2 (8.3-13.0)	11.8 $\pm$ 1.3 (9.0-13.7)	11.6 $\pm$ 1.2 (8.3-13.0)
3 Absolute VO _{2MAX} (l/min)	4.75 $\pm$ 0.8 (3.1-5.5)	4.8 $\pm$ 0.8 (3.0-5.5)	4.8 $\pm$ 0.7 (3.1-5.7)
4 Relative VO _{2MAX} (ml/kg/min)	64.2 $\pm$ 5.19 (53.8-74.0)	65.4 $\pm$ 6.4 (55.0-80.6)	63.9 $\pm$ 6.9 (54.8-78.6)
5 W _{MAX} (W)	351.3 $\pm$ 57.4 (230-410)	363.3 $\pm$ 57.6 (250-428)	362.6 $\pm$ 48.0 (230-410)
6 W _{MAX} /m _b (W/kg)	4.8 $\pm$ 0.3 (4.0-5.2)	4.9 $\pm$ 0.3 (4.5-5.6)	4.9 $\pm$ 0.3 (4.1-5.3)
7 W _{MAX} /m _c (W/kg)	4.2 $\pm$ 0.3 (3.4-4.7)	4.3 $\pm$ 0.4 (3.8-4.9)	4.3 $\pm$ 0.3 (3.4-4.6)

TTT Speed = average uphill time-trial speed; SDP TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Table 7. Air temperature, relative humidity, and wind speeds encountered during the three uphill time-trials (May, July, September 2001).

	Air Temperature	Relative Humidity	Wind Speed Ranges*	
			Minimum	Maximum
Time-trial #1	68° F	31.0%	0-4 MPH	7-15 MPH
Time-trial #2	75° F	26.0%	0-6 MPH	10-14 MPH
Time-trial #3	72° F	12.5%	0-5 MPH	15-20 MPH

*Minimum wind speeds were encountered during the first sheltered two-thirds of the time trial course. Maximum wind speeds were encountered at the more exposed summit-finish of the time-trial course.

The correlations between average time-trial speed and SDP time-to-exhaustion were very high for all trials ($r = 0.85$ to 0.90), as were the correlations between average time-trial speed and W_{MAX}/m_c ($r = 0.83$ to 0.92). Significant correlations were also observed between average time-trial speed and W_{MAX}/m_b ($r = 0.75$ to 0.90) and relative $\dot{V}O_{2MAX}$ ($r = 0.63$ to 0.73). Table 8 contains zero-order correlations between matched uphill time-trial and SDP performance measurements.

Table 8. Phase II correlations between average TT speed (m/s) and SDP performance variables.

	Trial 1 (n = 12)	Trial 2 (n = 11)	Trial 3 (n = 11)
1 SDP TTE (min)	0.86*	0.90*	0.85*
2 Absolute $\dot{V}O_{2MAX}$ (l/min)	0.55	0.70*	0.80*
3 Relative $\dot{V}O_{2MAX}$ (ml/kg/min)	0.73*	0.75*	0.63*
4 W_{MAX} (W)	0.53	0.68*	0.76*
5 W_{MAX}/m_b (W/kg)	0.75*	0.90*	0.77*
6 W_{MAX}/m_c (W/kg)	0.84*	0.92*	0.83*

*Values differ significantly from zero, $P < 0.05$. TTE = laboratory protocol time-to-exhaustion; $\dot{V}O_{2MAX}$ = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

The correlation between change in average time-trial speed and change in SDP time-to-exhaustion varied from $r = 0.26$ to 0.87 , but the correlation between average time-trial speed and W_{MAX}/m_c was consistently high ($r = 0.71$ to 0.90), as was the correlation between average time-trial speed and W_{MAX}/m_b ($r = 0.70$ to 0.90). Interestingly, change-scores involving Trial 1 (1-2 and 1-3) were consistently lower than change-scores not involving Trial 1 (2-3). Table 9 contains zero-order correlations among inter-trial changes in uphill time-trial and SDP performance variables.

Table 9. Phase II correlations between inter-trial changes in average TT speed (m/s) and SDP performance variables.

		Trials 1-2	Trials 2-3	Trials 1-3	Trials 1-2-3
1	SDP TTE (min)	0.57	0.87*	0.26	0.54*
2	Absolute VO_{2MAX} (l/min)	0.23	0.56	0.60	0.54*
3	Relative VO_{2MAX} (ml/kg/min)	0.47	0.72*	0.66	0.67*
4	W_{MAX} (W)	0.70*	0.85*	0.48	0.63*
5	W_{MAX}/m_b (W/kg)	0.73*	0.90*	0.71*	0.75*
6	W_{MAX}/m_c (W/kg)	0.74*	0.90*	0.70*	0.75*

*Values differ significantly from zero, $P < 0.05$. TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Scatterplots depicting the relationships between inter-trial change in average time-trial speed and W_{MAX}/m_c are provided in Figures 3-6. Notice that W_{MAX}/m_c was sensitive to both positive *and* negative changes in uphill time-trial performance (as were W_{MAX} and W_{MAX}/m_b). Also, the y-intercepts of the least-squares derived linear regressions for average time-trial speed are all very close to zero.

Figure 3. Scatterplot depicts the relationship between Trial 1 and Trial 2 changes (T2-T1) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.001 + 0.522 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.55$.

Figure 4. Scatterplot depicts the relationship between Trial 2 and Trial 3 changes (T3-T2) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.066 + 0.928 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.81$.

Figure 5. Scatterplot depicts the relationship between Trial 1 and Trial 3 changes (T3-T1) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: $\text{speed (m/s)} = 0.066 + 0.928 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.81$.

Figure 5. Scatterplot depicts relationship between changes for all trials (1-2, 2-3, 1-3) in uphill average time-trial speed (m/s) and W_{MAX} (W/kg). Solid line is least-squares derived linear regression: $\text{speed (m/s)} = 0.005 + 0.727 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.56$.

CHAPTER FIVE

DISCUSSION

Phase I

Although Heil and colleagues (2001) reported significant correlations between SDP performance and uphill time-trial performance ($r = 0.97$ to 0.98), the reliability of the SDP had yet to be established. Therefore, Phase I of the present study was undertaken to assess the intraclass reliability of the primary SDP performance measures. Results indicate that all SDP performance (TTE and W_{MAX}) and physiological (HR_{MAX} , and relative $\dot{V}O_{2MAX}$) measures were highly reliable, with intraclass correlation coefficients ranging from $R = 0.933$ to 0.992 .

No learning or other test order effects were detected during the three different SDP trials. The intraclass correlation coefficients for SDP performance for subjects with no prior maximal testing experience ($n = 12$) were actually equal to or higher than the intraclass correlation coefficients for subjects with prior maximal testing experience ($n = 9$). Additionally, single-score reliability for all subjects ($n = 21$) was very high for TTE ($R_{k=1} = 0.823$), W_{MAX} ($R_{k=1} = 0.908$), and $\dot{V}O_{2MAX}$ ($R_{k=1} = 0.977$).

The inter-trial CV for W_{MAX} (1.74%) is in agreement with previously reported CV values for peak power output (PPO). For instance, Balmer, Davison, and Bird (2000) reported a CV of 1.32% for PPO during a 16.1-km laboratory time-trial, and Lindsay et al. (1996) reported a CV of 1.30% for PPO during a 40-km laboratory time-trials. In

addition, the CV for SDP TTE (1.49%) was considerably lower than the CV for TTE determined by Krebs and Powers (1989) (5.2-55.9%) and McLellan et al. (1995) (2.8-31%) when studying untrained subjects cycling to fatigue at 80% $\dot{V}O_{2MAX}$, as well as that by Jeukendrup et al. (1996) (17%-40%) for well-trained subjects cycling to fatigue at 85% $\dot{V}O_{2MAX}$. The CV for SDP TTE was also marginally lower than the CV reported for TTC by Jeukendrup et al. (1996) (3.35%) and Bishop (1997) (2.7%) during fixed duration protocols of sixty minutes.

Phase II

In support of Heil et al. (2000), Phase II results served to re-validate the SDP as an accurate means to predict uphill time-trial performance. TTE and W_{MAX}/m_c were highly correlated with average uphill time-trial speed ($r = 0.85$ to 0.90 and $r = 0.83$ to 0.92 , respectively) for all three testing periods (May, July, and September 2001), as were W_{MAX}/m_b ($r = 0.75$ to 0.90) and relative $\dot{V}O_{2MAX}$ ($r = 0.63$ to 0.73). Once again, these values compare favorably with those previously reported in the literature (Balmer et al., 2000; Bishop et al., 1998; Hawley and Noakes, 1992; Lindsay et al., 1996; Schabort et al., 2000).

However, the primary purpose of the present study was to determine the ability of the SDP to track *changes* in uphill time-trial performance. Change-score correlations between average time-trial speed and W_{MAX}/m_b and W_{MAX}/m_c were significant for all three testing periods ($r = 0.70$ - 0.90 and $r = 0.71$ - 0.90 , respectively), explaining 50% to 80% of the variance of inter-trial changes in average time-trial speed. Notably, change-

score correlations associated with Trial 1 uphill time-trial data (Trial 1-2, 1-3) were consistently lower than change-score correlations associated with Trials 2-3. This is likely due to the fact that several of the subjects rode the Trial 1 uphill time-trial “blind” (with no prior reconnaissance), resulting in inter-trial learning effects. Also, Trial 3 environmental conditions (wind speed in particular) likely had an affect on change-score correlations for Trials 1-3. Despite these circumstances, however, correlations for change-scores between Trials 1-2 and 1-3 were still relatively favorable, (though not as high as correlations for change-scores between Trials 2-3). Furthermore, absolute and relative measures of W_{MAX} were sensitive to both positive and negative changes (increases and decreases) in average uphill time-trial speed, as depicted in Figures 3-6.

In contrast, Lindsay et al. (1996) failed to note significant change-score correlations between W_{MAX}/m_b and flat 40-km time-trial performance before and after a four-week period of high-intensity interval training (despite significant improvements in both dependent variables). The reason for these results is likely due to the design of the incremental test employed by Lindsay and coworkers. The protocol commenced at a work rate equivalent to 3.33 W/kg body mass (m_b) for 150 seconds, then increased by 50 W for another 150 seconds. Following stage two, the exercise intensity was increased by 25 W every 150 seconds until volitional exhaustion – *regardless of body mass and/or the theoretical energy demands of flat 40-km time-trial cycling.*

Whereas the SDP was specifically designed to simulate the external power demand (W_D) of uphill cycling as influenced by body mass (e.g. $W_D \propto M_B^{0.89}$, Heil, 1998), the protocol used by Lindsay et al. failed to accurately simulate the power demand

of flat 40-km cycling ($W_D \propto M_B^{0.32}$; Swain, 1994). It is not surprising, therefore, that changes in PPO failed to correlate with changes in 40-km time-trial performance.

Despite the high correlations observed in the present study between changes in SDP W_{MAX} and average time-trial speed, correlations between changes in SDP time-to-exhaustion and average time-trial speed were low to moderate ($r = 0.26$ to $.87$), explaining only 7% to 75% of the inter-trial variance. This discrepancy between two seemingly analogous measures of SDP performance can be explained by taking a closer look at the theoretical and structural design of the SDP.

The SDP was primarily designed to simulate the energy demand of uphill cycling as influenced by body mass. Stage 5 of the SDP is accordingly designated as the estimated power demand required for a person of a given body mass to propel a bicycle up a 8.7% (5°) incline at 6.72 m/s (15 MPH). This particular speed and grade were chosen to approximate a sub-lactate threshold power output in *moderately trained collegiate cyclists* (Heil et al, 2000).

At this point it is important to recognize a secondary purpose of the SDP: to serve as a valid and reliable $\dot{V}O_{2MAX}$ test for cyclists when appropriate. As such, the remaining SDP stages were designed to fit within the eight to twelve minute time period considered ideal for the determination of maximal cardiopulmonary capacity (Buchfuhrer et al., 1983). Stage 1 was arbitrarily calculated as 20% of the Stage 5 value, Stage 2 as 40%, Stage 3 as 60%, etc. Stages 6 and above increase by 10% increments of Stage 5.

Therefore, it is easy to understand why TTE is not as sensitive to changes in uphill time-trial performance as W_{MAX}/m_c . Whereas W_{MAX}/m_c is theoretically derived to

correlate highly with uphill time-trial performance, TTE is bound by the time limitations for the proper assessment of $\dot{V}O_{2MAX}$. Though unconfirmed, this trait is likely inherent to all PPO protocols designed with the secondary purpose to assess $\dot{V}O_{2MAX}$; measures of W_{MAX} will always correlate more strongly with performance than measures of TTE or TTC. A second factor potentially responsible for the low to moderate change-score correlations associated with TTE is the relatively lower reliability of TTE (when compared to W_{MAX} , Phase I).

There are several benefits of modeling the SDP after an uphill time-trial as opposed to a flat time-trial. In addition to significantly simplifying the underlying calculations of contributing factors to the overall energy demand of cycling (see Heil et al., 2000, Appendix), an uphill time-trial simulation may also be more relevant and valid for the prediction of overall professional cycling success.

Hills determine the outcome of a road race more than any other element. It is a basic function of time: even on circuit courses containing equal-length segments of positive and negative elevation gain, cyclists' overall time will be greater on the uphill (Kyle, 1988; Swain, 1997). Though larger cyclists may descend faster than smaller, climbing-proficient cyclists, they cannot make up the time lost going uphill (Swain, 1994). Additionally, the relative power-to-drag advantage of large cyclists on the flats (Swain, 1994) is effectively negated by the ability of smaller cyclists to remain tucked within the sheltering draft of the peloton (thus reducing their air resistance by as much as 40%, (McCole et al., 1990)). And once the road begins to climb again, the increased grade and slower speeds play conveniently to the talents of climbers. For these reasons,

victors of the predominantly hilly grand tours (Tour de France, Giro d'Italia, and the Vuelta a España) tend to be smaller, climbing-proficient cyclists (Swain, 1994).

Consequently, a laboratory protocol capable of predicting and/or tracking changes in uphill time-trial performance may also predict cycling success on a higher level.

CHAPTER SIX

CONCLUSION

The SDP appears to be a reliable and valid means for predicting and tracking uphill time-trial cycling performance. Phase I results indicate that the primary measures of SDP performance, W_{MAX}/m_c and TTE, were highly reproducible. W_{MAX}/m_c had an intraclass correlation coefficient of $R = 0.933$ and a single-score reliability of $R_{k=1} = 0.986$. TTE had an intraclass correlation coefficients of $R = 0.992$ and a single-score reliability of $R_{k=1} = 0.973$. The correlations of variation for W_{MAX}/m_c and TTE were 1.74% and 1.49%, respectively.

Phase II results indicate that W_{MAX}/m_c is a valid measure for tracking changes in uphill time-trial performance. Change-score correlations for W_{MAX}/m_c and average uphill time-trial speed were consistently high ($r = 0.74$ to 0.90). SDP TTE, however, appears less able to track changes in average uphill time-trial speed ($r = 0.26$ to 0.87). This is likely due to the structural design of the SDP stages (resistance levels).

Implications for Further Research

Given the practicality, affordability, and promising ability of the SDP to predict and track changes in uphill time-trial performance in a heterogeneous group of cyclists (with respect to gender, age, and competitive experience) it would be of benefit for future studies to validate the SDP in more homogeneous populations: more highly trained adults

and non-trained to highly trained youth populations. The latter would be especially important for youth cycling talent identification programs. Also, considering the variable and inhospitable environmental conditions encountered during Phase II of the present study (welcome to Bozeman, MT), it would be advisable for future researchers to conduct a similarly designed study in a more climatically moderate location.

REFERENCES

Acevedo, E.O., and Goldfarb, A.H. (1989). Increased training intensity effects on plasma lactate, ventilatory threshold, and endurance. Medicine and Science in Sports and Exercise, 21(5), 563-568.

Allen, W.K., Seals, D.R., Hurley, B.F., Ehsani, A.A., and Hagberg J.M. (1985). Lactate threshold and distance running performance in young and older endurance athletes. Journal of Applied Physiology, 58, 1281-1284.

Astrand, P.O. and Rodahl, K. (1986). Textbook of Work Physiology, 3rd edition. New York: McGraw-Hill.

Aunola, S., and Rusko, H. (1986). Aerobic and anaerobic thresholds determined from venous lactate or from ventilation and gas exchange in relation to muscle fiber composition. International Journal of Sports Medicine, 7, 161-166.

Balmer, J., Davison, R.C., and Bird, S.R. (2000). Peak power predicts performance power during an outdoor 16.1-km cycling time trial. Medicine and Science in Sports and Exercise, 32(8), 1485-1490.

Barlow, K., Weltman, A., Schurrer, R., and Henritze, J. (1985). Prediction of maximal effort bicycle ergometer endurance performance. International Journal of Sports Medicine, 6(4), 190-196.

Bassett, D.R. and Howley, E.T. (2000). Limiting factors for maximum oxygen uptake and determinants of endurance performance. Medicine and Science in Sports Exercise, 32(1), 70-84.

Basset, D.R. and Howley, E.T. (1997). Maximal oxygen uptake: "classical" versus "contemporary" viewpoints. Medicine and Science in Sports Exercise, 29, 591-603.

Bassett, D.R., Kyle, C.R., Passfield, L., Broker, J.P., and Burke, E.R. (1999). Comparing cycling world hour records, 1967-1996: modeling with empirical data. Medicine and Science in Sports Exercise, 31, 1665-1676.

Beaver, W.L., Wasserman, K., and Whipp, B.J. (1985). Improved detection of lactate threshold during exercise using a log-log transformation. Journal of Applied Physiology, 59, 1936-1940.

Bilodeau B., Rundell K.W., Roy B., and Boulay M.R. (1996). Kinematics of cross-country ski racing. Medicine and Science in Sports and Exercise, 28(1), 128-138.

Billat, V. Renoux, J.C., Pinoteau, J., Petit, B., and Koralsztein, J.P. (1994). Reproducibility of running time to exhaustion at $\text{VO}_{2\text{MAX}}$ in subelite runners. Medicine and Science in Sports and Exercise, 26(2), 254-257.

- Bishop, D. (1997). Reliability of a 1-hour endurance performance test in trained female cyclists. Medicine and Science in Sports and Exercise, 29, 554-559.
- Bishop, D. Jenkins, D.G., and MacKinnon, L.T. (1998). The relationship between plasma lactate parameters, W_{peak} , and 1-h cycling performance in women. Medicine and Science in Sports and Exercise, 30, 1270-1275.
- Borysewicz, E. (1985). Bicycle Road Racing: Complete Program for Training and Competition, Brattleboro, VT: Vitesse Press, pp. 270.
- Bourdon, P. (2000). Blood Lactate Transition Thresholds: Concepts and Controversies. In: Physiological Tests for Elite Athletes. Champaign, IL: Human Kinetics.
- Brooks, G.A., Fahey, T.D., and White, T.P. (1996). Exercise Physiology: Human Bioenergetics and Its Applications, 2nd edition. CA: Mayfield Publishing Company.
- Buchfurher, M.J., Hansen, J.E., Robinson, T.E., Sue, D.Y., Wasserman, K. and Whipp, B.J. (1983). Optimizing the exercise protocol for cardiopulmonary assessment. Journal of Applied Physiology, 55, 558-564.
- Burke, E.R. (1995). Serious Cycling. Champaign, IL: Human Kinetics.
- Burnham, T.R., Fox, S., and Wilcox, A. (1995). The reproducibility of cycling time to volitional fatigue. Medicine and Science in Sports and Exercise, 27, S15.
- Cheng, B., Kuipers, H., Snyder, A., et al. (1992). A new approach for the determination of ventilatory and lactate thresholds. International Journal of Sports Medicine, 13, 518-522.
- Coggan, A.R. and Coyle E.F. (1987). Reversal of fatigue during prolonged exercise by carbohydrate infusion or ingestion. Journal of Applied Physiology, 63, 2388-2395.
- Conconi, F., Ferrara, M., Ziglio, P.G. Droghetti, P., and Codeca, L. (1982). Determination of the anaerobic threshold by a noninvasive field test in runners. Journal of Applied Physiology, 52, 869-873.
- Conley, D.L, and Krahenbahl, G.S. (1980). Running economy and distance running performance of highly trained athletes. Medicine and Science in Sports and Exercise, 12, 357-360
- Costill, D.L. (1967). The relationship between selected physiological variables and distance running performance. Journal of Sports and Physical Fitness, 7, 61-66.

Costill, D.L. and Fox, E. (1969). Energetics of marathon running. Medicine and Science in Sports and Exercise, 1, 81-86.

Costill, D.L. Bowers, R., Braham, G., and Sparks, K. (1971a). Muscle glycogen utilization during prolonged exercise on successive days. Journal of Applied Physiology, 31, 834-838.

Costill, D.L., Kovaleski, J., Porter, D., Kirwan, J., Fielding, R., and King, D. (1985). Energy expenditure during front crawl swimming: predicting success in middle distance events. International Journal of Sports Medicine, 6, 266-270.

Costill, D.L., Sparks, K., Gregor, R. and Turner, C. (1971b). Muscle glycogen utilization during exhaustive exercise. Journal of Applied Physiology, 31, 353-356.

Costill, D.L., Thomason, H., and Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. Medicine and Science in Sports and Exercise, 5, 248-252.

Coyle, E.F. Coggan, A.R., Hopper, M.K., and Wlaters, T.J. (1988). Determinants of endurance in well-trained cyclists. Journal of Applied Physiology, 54, 18-23.

Coyle, E.F., Feltner, M.E., Kautz, S.A., Hamilton, M.T., Montain, S.J., Baylor, A.M., Abraham, L.D., and Petrek, G.W. (1991). Physiological and biomechanical factors associated with elite endurance cycling performance. Medicine and Science in Sports and Exercise, 23(1), 93-107.

Craig, N.P., Norton, K.I., Bourdon, P.C., Woolford, S.M., Stanef, T., Squires, B., Olds, T.S., Conyers, R.A.J., and Walsh, C.B.V. (1993). Aerobic and anaerobic indices contributing to track endurance cycling performance. European Journal of Applied Physiology, 67, 150-158.

Daniels, J. (1974). Physiological characteristics of champion male athletes. Research Quarterly for Exercise and Sport, 45, 342-348.

Davis, H.A., Basset, J., Hughes, P., et al. (1983). Anaerobic threshold and lactate turnpoint. European Journal of Applied Physiology, 50, 383-392.

Davison, R.C., Swan, D., Coleman, D., and Bird, S. (2000). Correlates of simulated hill climb cycling performance. Journal of Sports Sciences, 18, 105-110.

Dengel, D.R., Flynn, M.G., and Costill, D.L. (1989). Determinants of success during triathlon competition. Research Quarterly for Exercise and Sport, 60, 234-238.

- Dillman, C.J. (1975). Kinematic analysis of running. Exercise and Sport Science Reviews, 3, 193-218.
- di Prampero, P.E., Cortilli, G., Mognoni, P., Saibene, F. (1979). Equation of motion of a cyclist. Journal of Applied Physiology, 47, 201-206
- El-Sayed, M.S., Balmer, J., and Rattu, A.J.M. (1997). Carbohydrate ingestion improves endurance performance during 1 hour simulated cycling time trial. Journal of Sports Science, 15, 223-230.
- Farrell, P.A. , Wilmore, J.H., Coyle, E.F., Billing, J.E., and Costill, D.L. (1979). Plasma lactate accumulation and distance running performance. Medicine and Science in Sports and Exercise, 11, 338-344.
- Foster, C., Costill, D.L., Daniels, J.T., and Fink, W.J. (1978). Skeletal muscle enzyme activity, fiber composition, and VO_{2MAX} in relation to distance running performance. European Journal of Applied Physiology, 39, 73-80.
- Foster, C., Green, M.A., Snyder, A.C., and Thompson, N.N. (1993). Physiological responses during simulated competition. Medicine and Science in Sports and Exercise, (25)7, 877-882.
- Hagberg, J.M. and Coyle, E.F. (1983). Physiological determinants of endurance performance as studied in competitive racewalkers. Medicine and Science in Sports and Exercise, 15, 287-289.
- Hagberg, J.M., Mullin, J.P., Bahrkre, M., and Limburg, J. (1979). Physiological profiles and selected psychological characteristics of national class American cyclists. Sports Medicine, 19, 341-346.
- Hawley, J.A., and Noakes, T.D. (1992). Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. European Journal of Applied Physiology, 65, 79-83.
- Heck, H., Mader, A., Hess, G., et al. (1985). Justification of the 4 mmol/l lactate threshold. International Journal of Sports Medicine, 6, 117-130.
- Heil, D.P. (1997). The pressor response to submaximal cycle ergometry while using aerodynamic handlebars. International Journal of Sports Medicine, 18(1), 1-7.
- Heil, D.P. (1998). Scaling of submaximal oxygen uptake with body mass and combined mass during uphill treadmill bicycling. Journal of Applied Physiology, 85, 1376-1383.

Heil, D.P., Derrick, T.R., and Whittlesey, S. (1997). The relationship between preferred and optimal positioning during submaximal cycle ergometry. European Journal of Applied Physiology, 75, 160-165.

Heil, D.P., Murphy O.F., Mattingly, A.R., and Higginson, B.K. (2000). Prediction of uphill time-trial bicycling performance with a scaling derived protocol. European Journal of Applied Physiology, 85, 374-382.

Heil, D.P., Wilcox, A., and Quinn, C. (1995). The effect of seat-tube angle variation on cardiorespiratory responses during submaximal bicycling. Medicine and Science in Sports and Exercise, 27(5), 730-735.

Hickey, M.S., Costill, D.L., McConell, G.K., Widrick, J.J., and Tanaka, H. (1992). Day to day variation in time trial cycling performance. International Journal of Sports Medicine, 13, 467-470.

Hickson, R.C., Dvorak, B.A., Gorostiaga, E.M., Kurowski, T.T., and Foster, C. (1988). Potential for strength and endurance training to amplify endurance performance. Journal of Applied Physiology, 65, 2285-2290.

Hill, A.V. and Lupton, H. (1923). Muscular exercise, lactic acid, and the supply and utilization of oxygen. Quarterly Journal of Medicine, 16, 135-171.

Hopkins, S.R. and McKenzie, D.C. (1994). The laboratory assessment of endurance performance in cyclists. Canadian Journal of Applied Physiology, 19, 266-274.

Hopkins, W.G., Hawley, J.A., and Burke, L.M. (1999). Design and analysis of research on sport performance enhancement. Medicine and Science in Sports and Exercise, 31, 472-485.

Jacobs, I. (1986). Blood lactate: implications for training and sport performance. Journal of Sports Medicine, 3, 10-25.

Jeukendrup, A., Saris, W.H.M., Boruns, F., and Kester, A.D.M. (1996). A new validated endurance performance test. Medicine and Science in Sports and Exercise, 28, 266-270.

Kautz, S.A., Feltner, M.E., Coyle, E.F., and Baylor, A.M. (1991). The pedaling technique of elite endurance cyclists: changes with increasing workload at constant cadence. International Journal of Sports Biomechanics, 7, 29-53.

Kindermann, W., Simon, G., and Keul, J. (1979). The significance of the aerobic-anaerobic transition for the determination of work load intensities during training. European Journal of Applied Physiology, 42, 25-34.

- Krebs, P.S. and Powers, S.K. (1989). Reliability of laboratory performance tests. Medicine and Science in Sports and Exercise, 31, S10, 1989.
- Kuipers, H., Verstappen, F.T.J., Keizer, P., Geurten, P., and Van Krannenburg, G. (1985). Variability of aerobic performance in the laboratory and its physiologic correlates. International Journal of Sports Medicine, 6, 197-201.
- Kumagai, S., Tanaka, K., Matsumura, Y., Matsuzaka, A., Hirakoba, K., and Yasuda, H. (1982). Relationships of the anaerobic threshold with the 5 km, 10 km, and 10 mile races. European Journal of Applied Physiology, 42, 13-23.
- Kyle, C.R. (1988). The mechanics and aerodynamics of cycling. In: Medical and Scientific Aspects of Cycling, Burke, E.R. and Newsome, M.M (Eds.). Champaign, IL: Human Kinetics, 235-251.
- Lindsay, F.H., Hawley, J.A., Myburgh, K.H., Schomer, H.H., and Noakes, T.D. (1996). Improved athletic performance in highly trained cyclists after interval training. Medicine and Science in Sports and Exercise, 28, 1427-1434.
- Loftin, M. and Warren, B. (1994). Comparison of a simulated 16.1-km time trial, VO_{2MAX} and related factors in cyclists with different ventilatory thresholds. International Journal of Sports Medicine, 15(8), 498-503.
- MacRae, H.S.H., Hise, K.J., and Allen, P.J. (2000). Effects of front and dual suspension mountain bike systems on uphill cycling performance. Medicine and Science in Sports and Exercise, 29(11), 1505-1512.
- McLellan, T.M., Cheung, S.S., and Jacobs, I. (1995). Variability of time to exhaustion during submaximal exercise. Canadian Journal of Applied Physiology, 20, 39-51.
- Miller F.R. and Manfredi, T.G. (1987). Physiological and anthropometrical predictors of 15 kilometer time trial cycling performance time. Research Quarterly for Sport and Exercise, 58, 250-254.
- McCole, S.D., Claney, K. Conte, J.C., Anderson, R., and Hagberg, J.M. (1990). Energy expenditure during bicycling. Journal of Applied Physiology, 68, 748-753.
- Morgan, D.W., Baldini, F.D., Martin, P.E., and Kohrt, W.M. (1989). Ten kilometer performance and predicted velocity at VO_{2MAX} among well-trained male runners. Medicine and Science in Sport and Exercise, 18, 78-83.
- Nichols, J.F., Phares, S.L., and Buono, M.J. (1997). Relationship between blood lactate response to exercise and endurance performance in competitive female master cyclists. International Journal of Sports Medicine, 18, 458-463.

Noakes, T.D. (1988). Implications of exercise testing for prediction of athletic performance: a contemporary perspective. Medicine and Science in Sport and Exercise, 20, 319-330.

Noakes, T.D., Myburgh, K.H., and Schall, R. (1990). Peak treadmill velocity during the $\text{VO}_{2\text{peak}}$ test predicts running performance. Journal of Sport Science, 8, 25-45.

Olds, T.S., Norton, K.I., Lowe, E.L.A., Olive, S., Reay, F., and Ly, S. (1995). Modeling road cycling performance. Journal of Applied Physiology, 78, 1596-1611.

Palmer, G.S., Clancy, M.C., Hawley, A., Rodger, I.M., Burke, L.M., and Noakes, T.D. (1998). Carbohydrate ingestion immediately before exercise does not improve 20-km time trial performance in well trained cyclists. International Journal of Sports Medicine, 19, 415-418.

Palmer, G.S., Dennis, S.C., Noakes, T.D., and Hawley, J.A. (1996). Assessment of the reproducibility of performance testing on an air-braked cycle ergometer. International Journal of Sports Medicine, 17, 293-298.

Powers S.K., Dodd, S., Deason, R., Byrd, R., and McKnight, T. (1983). Ventilatory threshold, running economy, and distance running performance of trained athletes. Research Quarterly for Sport and Exercise, 54, 179-182.

Rundell K.W. and McCarthy, J.R. (1996). Effect of kinematic variables on performance in women during a cross-country ski race. Medicine and Science in Sports and Exercise, 28(11), 1413-1417.

Saltin B. and Astrand, P.O. (1967). Maximal oxygen uptake in athletes. Journal of Applied Physiology, 23, 353-358.

Schabort, E.J., Hawley, J.A., Hopkins, W.G., Mujika, I., and Noakes, T.D. (1998). A new reliable laboratory test of endurance performance for road cyclists. Medicine and Science in Sports and Exercise, 30(12), 1744-1750.

Scott, B.K. and Houmard, J.A. (1994). Peak running velocity is highly related to distance running performance. International Journal of Sports Medicine, 15, 504-507.

Sjodin, B. (1981). Onset of blood lactate accumulation and marathon running performance. International Journal of Sports Medicine, 2, 23-26.

Skinner J.S., and McLellan, T.M. (1980). The transition from aerobic to anaerobic metabolism. Research Quarterly for Exercise and Sport, 51, 234-248.

Sleivert, G.G. and Rowlands, D.S. (1996). Physical and physiological factors associated with success in the triathlon. International Journal of Sports Medicine, 22(1), 8-18.

Smith, J.C., Dangelmaier, B.S., and Hill, D.W. (1999). Critical power is related to cycling time trial performance. International Journal of Sports Medicine, 20, 374-378.

Swain, D. P. (1994). The influence of body mass in endurance bicycling. Medicine and Science in Sports and Exercise, 26(1), 58-63.

Swain, D.P. (1997). A model for optimizing cycling performance by varying power output on hill and in wind. Medicine and Science in Sports and Exercise, 29(8), 1104-1108.

Thoden, J. (1991). Testing aerobic power. In: Physiological Testing of the High-Performance Athlete, 2nd edition., Champaign, IL: Human Kinetics

Van Handel, P.J., Baldwin, C., Puhl, J., Katz, A., Dantine, S., and Bradley, P.W. (1988). Measurement and interpretation of physiological parameters associates with cycling performance. Burke, E.R. and Newsom, M.M. (eds.) Medical and Scientific Aspects of Cycling. Champaign, IL: Human Kinetics Publishers, 47-72.

Van Ingen Schenau G.J., de Groot G., and Hollander A.P. (1983). Some technical, physiological and anthropometrical aspects of speed skating. European Journal of Applied Physiology and Occupational Physiology, 50(3), 343-354.

Vincent, W.J. (1995). Statistics in Kinesiology, Champaign, IL: Human Kinetics, p. 179.

Weltman, J., Snead, D., and Stein, P. (1990) Reliability and validity of a continuous incremental treadmill protocol for the determination of lactate threshold, fixed blood lactate concentrations, and $\text{VO}_{2\text{MAX}}$. International Journal of Sports Medicine, 11, 26-32.

Westgarth-Taylor, C., Hawley, J.A., Rickard, S., Myburgh, K.H., and Noakes, T.D. (1997). Metabolic and performance adaptations to interval training. European Journal of Applied Physiology, 75, 298-304.

Weston, A.R., Myburgh, K.H., Lindsay, F.H., Dennis, S.C., Noakes, T.D., and Hawley, J.A. (1997). Skeletal muscle buffering and endurance performance after high-intensity interval training by well-trained cyclists. European Journal of Applied Physiology, 75, 7-13.

Williams K.R., and Cavanagh, P.R. (1987). Relationship between distance running mechanics, running economy, and performance. Journal of Applied Physiology, 63(3), 1236-1245.

Yoshida, T. (1984). Effect of dietary modifications on lactate threshold and onset of blood lactate accumulation during incremental exercise. European Journal of Applied Physiology, 53, 200-205.

Yoshida, T., Chida, M., Ichioka, M., and Suda, Y. (1987). Blood lactate parameters related to aerobic capacity and endurance performance. European Journal of Applied Physiology, 56, 7-11.

APPENDICES

APPENDIX A

SUBJECT CONSENT FORM

**SUBJECT CONSENT FORM FOR PARTICIPATION IN
HUMAN RESEARCH MONTANA STATE UNIVERSITY**

PROJECT TITLE: Reliability and validity of a test protocol to predict and track uphill cycling time-trial performance (Spring/Summer 2001)

FUNDING: This study is NOT a funded project.

PRINCIPLE INVESTIGATOR: Daniel P. Heil, PhD.
Assistant Professor, Exercise Physiology
Department of Health and Human Development
Romney 103, Montana State University
Bozeman, MT. 59715-3540

PROJECT DIRECTOR: Owen F. Murphy
Master's Degree Candidate
Department of Health and Human Development

PURPOSE OF THE STUDY: This investigation will be conducted in two parts. Part I of the study will assess the reliability of a laboratory-based test protocol (SDP) to predict a cyclist's uphill cycling time-trial performance capability. Part II of the study will subsequently determine the relationship between SDP performance and uphill time-trial performance. Please read and initial only the section(s) of this *Informed Consent Document* that apply to you (Part I, II, or both).

☐ **Part I.** The purpose of this phase of the investigation is to assess the test-retest reliability of a laboratory-based protocol called the SDP (Scaling Derived Protocol). This new protocol, based upon a previously published algorithm by the principle investigator, requires that each subject use their own road racing bicycle mounted on a stationary trainer (CompuTrainer™).

☐ **Part II.** The purpose of this phase of the investigation is to determine if the laboratory-based SDP test can reliably predict and track the actual uphill time-trial performance capability of a cyclist over a period of seven months.

Each subject is presented with this *Informed Consent Document* – the purpose of the document should be explained prior to your signing. Once signed, medical clearance will be obtained using a standard medical form (i.e. Physical Activity Readiness Questionnaire, or PAR-Q). If any questions arise concerning your medical history, medical clearance (in writing) may also be obtained from your physician. This procedure is in compliance with policies formulated by the American College of Sports Medicine¹.

¹ American College of Sports Medicine (2000). *ACSM's Guidelines for Exercise Testing and Prescription* (5th ed). Williams & Wilkins, Philadelphia, PA.

STUDY OUTLINE:

- ☐ **Part I.** You (the subject) will be required to make three visits to the Movement Science Laboratory (Romney Building, Room 2) at Montana State University (Bozeman) within a two-week period. The visits will last approximately 1.5 hours each, and will be scheduled 24-48 hours AFTER your last hard workout. It is important that you prepare for each lab visit as you would for a true cycling competition.

Before arriving at the lab, you should refrain from ingesting any medications, including caffeine or aspirin, for at least 2 hours. If any medications were taken (such as cold or allergy medicine) please inform the investigator PRIOR to any testing – we will gladly reschedule your visit. You should arrive at the lab prepared to engage in 12-15 of vigorous (maximal) exercise using your own road bicycle. Therefore, all subjects must bring their own bicycle, as well as cleats and appropriate exercise clothing.

One of the main purposes of your lab visits is to measure your maximal oxygen consumption (VO_{2MAX}). This test determines your body's maximal capability to uptake, transport, and then utilize oxygen in the working muscles while cycling on a stationary trainer. After measuring body weight and height, you will be allowed to warm up on your bicycle at a self-selected speed and grade for approximately 10-15 minutes (or until you feel comfortable with the testing environment). The test itself will start out easy, and gradually increase in difficulty every 1-2 minutes while you maintain a steady cadence between 80 and 90 RPM. The test will end when you literally cannot maintain the cadence any longer (approximately 10-15 minutes). The effort put forth at the highest intensity of exercise during the test is comparable to that of an 800-meter running race. *The goal of the test is for you to last as long as you possibly can into the protocol before you reach the point where you must stop.*

During the exercise test you will be breathing through a mouthpiece (similar to a snorkel mouthpiece) so that the amount of oxygen you are consuming can be measured. At the same time, you will be wearing a heart rate monitor strap around your chest to measure heart rate via telemetry. You may also be asked to provide a rating of your perceived exertion (RPE) on a scale of 0 to 10 (resting to maximal intensity exercise) during the test.

- ☐ **Part II.** If you haven't already done so, please read and initial the study outline for Part I. All of the laboratory testing involved in Part II of this investigation will be identical to that described above. In addition to performing a total of four bimonthly SDP tests, you (the subject) will be required to perform four corresponding outdoor uphill time trials. The corresponding laboratory and field tests will be scheduled to take place in the months of March, May, July, and September 2001, with a maximum

of 5 days separating the indoor and outdoor tests. Outdoor time trial dates will be scheduled 30 days in advance, with an alternative date arranged in the event of inclement weather.

The time trial course is 3.0 miles long, with an average gradient of 8%. Starting elevation is 4,270 feet, and maximum elevation is 5307 feet. The time trial course is located at the entrance to the Lewis and Clark Cavern State Park, approximately 50 miles west of Bozeman. Carpools to the test site will be arranged.

POTENTIAL RISKS: You should be aware that maximal exercise intensity (as experienced during the laboratory and field tests) may cause extreme fatigue immediately after the tests, and possibly during the next day. Maximal intensity exercise also involves a chance of precipitating a cardiac event (such as abnormal heart rhythms), or even death. However, the possibility of such an occurrence is slight (less than 1 in 10, 000) since you are in good physical condition with no known symptoms of heart disease, and since the tests will be administered by trained personnel. The measuring devices used for the laboratory tests (heart rate monitor and mouthpiece) may feel somewhat restricting and/or uncomfortable during testing, but all possible adjustments will be made to achieve the greatest amount of comfort for you. All possible precautions will be taken to ensure your safety make you feel comfortable before any testing takes place.

BENEFITS: A copy of each of your laboratory test results (VO_{2MAX}) will be provided for you. In addition, you may also request a copy of the results for the entire investigation (call the project director listed on the front page).

CONFIDENTIALITY: The data and personal information obtained from this study will be regarded as privileged and confidential. They will not be released except upon your written request/consent. Your right to privacy will be maintained in any ensuing analysis and/or presentation of the data by using coded identifications for each subject's data.

FREEDOM OF CONSENT: You may withdraw consent in writing, by telephone, or in person with either the principle investigator, Dr. Dan Heil, or the project director, Owen Murphy. Participation is completely voluntary. In the event of any physical injury occurring in connection with the conduct of this research, Montana State University will not provide any medical treatment or special compensation. We will, however, advise and assist the participant in receiving medical treatment. In addition, Montana State University will not be held responsible for injury or accidents the may occur when traveling to and from the laboratory and field test sites.

You are encouraged to express any questions, doubts, or concerns regarding this study. The investigators will attempt to answer all questions to the best of their ability. The investigators fully intend to conduct the study with your best interest, safety, and comfort in mind.

APPENDIX B

SDP TEST PROTOCOL

SDP stages (in watts) in 5.0 kg body mass increments. See text for details regarding the protocols derivation and administration.

Body Mass (kg)	Minute	1:00 -	2:00 -	4:00 -	6:00-	8:00-	9:00-	10:00-	11:00-	12:00-	13:00-	14:00-	15:00-	16:00-
	0-0:59	1:59	3:59	5:59	7:59	8:59	9:59	10:59	11:59	12:59	13:59	14:59	15:59	16:59
	Stage 1	2	3	4	5	6	7	8	9	10	11	12	13	14
40 - 44.9	32	64	97	129	161	177	193	209	225	241	258	274	290	306
45 - 49.9	36	71	107	142	178	196	213	231	249	267	284	302	320	338
50 - 54.9	39	77	117	155	194	214	233	253	272	291	311	330	350	369
55 - 59.9	42	84	126	168	211	232	253	274	295	316	337	358	379	400
60 - 64.9	45	91	136	181	227	250	272	295	318	340	363	386	408	431
65 - 69.9	49	97	146	194	243	267	292	316	340	364	389	413	437	462
70 - 74.9	52	104	155	207	259	285	311	337	362	388	414	440	466	492
75 - 79.9	55	110	165	220	275	302	330	357	385	412	440	467	495	522
80 - 84.9	58	116	174	232	291	320	349	378	407	436	465	494	523	552
85 - 89.9	61	122	184	245	308	337	368	398	428	459	490	520	551	582
90 - 94.9	64	129	193	257	321	354	386	418	450	482	515	547	579	611
95 - 99.9	67	135	202	270	337	371	404	438	472	506	540	573	607	640
100 - 104.9	71	141	211	282	352	388	423	458	493	529	564	599	634	670
105 - 109.9	74	147	221	294	368	404	441	478	515	552	588	625	662	699

APPENDIX C

PHASE II DATA

Table 10. Phase II, Trial 1 uphill time-trial and SDP performance measures (May 2001).

ID#	TT Time (min)	TT Speed (m/s)	SDP TTE (min)	VO _{2MAX} (l/min)	VO _{2MAX} (ml/kg/min)	W _{MAX} (W)	W _{MAX} /m _b (W/kg)	W _{MAX} /m _c (W/kg)
1	22.13	3.64	8.33	3.07	53.80	230.00	4.02	3.37
2	18.33	4.39	11	4.76	65.18	340.00	4.64	4.08
3	15.18	5.3	12.7	5.18	73.98	354.00	5.06	4.43
4	17.08	4.71	11.7	4.69	65.50	354.00	4.95	4.34
5	18.6	4.33	11	3.56	64.70	250.00	4.59	3.95
6	18.4	4.37	11.15	5.12	66.41	364.50	4.73	4.06
7	15.98	5.03	13	5.38	67.21	410.00	5.16	4.63
8	18.58	4.33	11.67	5.49	64.78	400.00	4.72	4.22
9	17.37	4.63	11	5.35	65.20	380.00	4.62	4.12
10	20	4.02	11	4.96	59.80	380.00	4.58	4.04
11	16.97	4.74	12	5.20	66.69	410.00	5.24	4.65
12	16.65	4.83	11.17	4.23	57.21	343.00	4.65	4.15
Ave	17.94	4.53	11.31	4.57	64.21	351.29	4.75	4.17
(SD)	(1.86)	(0.45)	(1.16)	(0.76)	(5.19)	(57.42)	(0.33)	(0.34)

TT Time = uphill time-trial time to completion; TT speed = average uphill time-trial speed; SDP TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Table 11. Phase II, Trial 2 uphill time-trial and SDP performance measures (July 2001).

ID#	TT Time (min)	TT Speed (m/s)	SDP TTE (min)	VO _{2MAX} (l/min)	VO _{2MAX} (ml/kg/min)	W _{MAX} (W)	W _{MAX} /m _b (W/kg)	W _{MAX} /m _c (W/kg)
1	21.5	3.74	9.00	3.03	55.01	250.00	4.50	3.76
2	18.32	4.39	12.00	4.84	65.37	360.00	4.88	4.30
3	14.47	5.56	13.67	5.51	80.58	382.00	5.58	4.87
5	17.93	4.49	12.00	3.67	67.89	270.00	5.00	4.30
6	18.62	4.32	10.57	5.13	66.64	347.00	4.51	3.87
7	15.6	5.16	13.58	5.21	65.11	427.50	5.31	4.78
8	16.7	4.82	12.33	5.23	63.83	420.00	5.14	4.58
9	16.05	5.01	12.00	5.51	67.89	410.00	5.06	4.51
11	19.62	4.1	11.00	4.99	60.87	380.00	4.62	4.08
12	16.97	4.74	11.67	4.45	59.36	353.30	4.74	4.23
13	15.73	5.11	12.33	5.31	66.39	397.00	4.93	4.44
Ave	17.41	4.68	11.83	4.81	65.36	363.35	4.93	4.34
(SD)	(2.04)	(0.53)	(1.32)	(0.80)	(6.43)	(57.62)	(0.33)	(0.35)

TT Time = uphill time-trial time to completion; TT speed = average uphill time-trial speed; SDP TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Table 12. Phase II, Trial 3 uphill time-trial and SDP performance measures (September 2001).

ID#	TT Time (min)	TT Speed (m/s)	SDP TTE (min)	VO ₂ MAX (l/min)	VO ₂ MAX (ml/kg/min)	W _{MAX} (W)	W _{MAX} /m _b (W/kg)	W _{MAX} /m _c (W/kg)
1	22.13	3.64	8.33	3.07	54.84	230.00	4.11	3.43
2	19.95	4.04	11.40	4.47	58.09	346.70	4.52	4.00
3	15.1	5.33	13.00	5.34	78.59	360.00	5.27	4.60
4	16.77	4.8	12.08	4.81	69.71	362.50	5.25	4.59
6	17.48	4.6	11.17	5.01	65.11	365.00	4.72	4.06
7	15.92	5.06	11.90	4.58	56.58	387.00	4.76	4.29
9	15.63	5.15	12.00	5.73	69.87	410.00	5.02	4.47
10	17.77	4.53	11.33	5.05	64.69	390.00	5.05	4.42
11	17.15	4.69	12.33	5.08	64.31	396.67	5.02	4.46
12	16.92	4.86	11.83	4.46	61.05	356.67	4.90	4.36
13	15.95	5.05	11.78	4.91	60.21	383.50	4.71	4.24
Ave	17.34	4.70	11.56	4.77	63.91	362.55	4.85	4.26
(SD)	(2.06)	(0.50)	(1.18)	(0.68)	(6.92)	(48.04)	(0.34)	(0.34)

APPENDIX D

JOURNAL MANUSCRIPT

(for submission to Medicine and Science in Sports and Exercise)

ABSTRACT

The ability to accurately quantify and predict endurance performance is imperative when assessing the effect of training interventions, dietary regimes, equipment modifications, and/or alterations in athlete position or technique. Due to the invasive nature and excessive costs of traditional physiological and biomechanical determinants of endurance performance ($\dot{V}O_{2\text{MAX}}$, lactate threshold, etc.), performance-based determinants of performance have received considerable attention. **Purpose:** To determine the ability of a previously validated (Heil et al., 2000) scaling-derived cycle ergometer protocol (SDP) to track changes in uphill time-trial (TT) cycling performance. **Methods:** Local competitive cyclists participated in either two ($n = 6$) or three ($n = 7$) testing periods separated by a minimum of ten weeks (May, July, September 2001). Each testing period consisted of an outdoor uphill TT (5-km, 8% grade) followed within ten days by a laboratory-based SDP. Longitudinal inter-trial changes in average TT speed (m/s) were compared with longitudinal inter-trial changes in SDP time-to-exhaustion (TTE, min) and relative SDP maximal power output (W_{MAX} , $\text{watts}\cdot\text{kg}^{-1}$). **Results:** Very high correlations were observed between inter-trial changes in average TT speed and relative W_{MAX} ($r = 0.70\text{-}0.94$). Correlations between inter-trial changes in average TT speed and TTE were generally lower and more variable ($r = 0.26\text{-}0.87$). **Conclusions:** These results suggest that changes in relative SDP W_{MAX} can validly and practically track changes in uphill TT performance. These results should be of benefit to cyclists, coaches, and sport scientists as they attempt to maximize endurance performance. This should ultimately lead to more effective cycling and youth talent identification programs for cycling.

Introduction

The sport of professional cycling is more competitive now than ever. Financial stakes are higher, race profiles are more demanding, and the difference between winning and losing is often decided by the smallest of margins. As a result, today's top cyclists and coaches are embracing a more scientific approach towards racing and training, including the regular use of laboratory-based performance testing.

According to MacDougall, Wenger, and Green (1991), performance testing of athletes serves a number of important functions: 1) it indicates the athlete's strengths and weaknesses, providing baseline data for individual training prescriptions; 2) it provides valuable feedback, allowing one to assess the effectiveness of a particular training program, diet, or piece of equipment; 3) it provides information regarding the health status of the athlete; 4) it is an educational process by which the athlete learns to better understand his or her body and the demands of the sport. As such, legitimate performance tests must be reliable, valid, and sensitive to small changes in an athlete's fitness level (Balmer, Davison, and Bird, 2000). Ideally, performance tests should also be affordable, available to the general public, and easy to administer.

The classical and most common endurance performance test employs a continuous submaximal workload (60-90% of $\dot{V}O_{2MAX}$) until volitional exhaustion (Jeukendrup et al., 1996). Despite reasonable correlations between time-to-exhaustion (TTE) and actual endurance performance (Acevedo and Goldfarb, 1989; Billat et al., 1988; Burnham et al., 1995; Coggan and Coyle, 1987; Coyle et al., 1988; Hickson et al.,

1988), the test-retest reliability of such protocols is suspect (Jeukendrup et al., 1996; Krebs and Powers, 1989; McLellan et al., 1995). For instance, Krebs and Powers (1989) and McLellan et al. (1995) independently determined coefficients of variation (CV) ranging from 2.8% to 55.9% in untrained subjects cycling to fatigue at 80% $\dot{V}O_{2\text{MAX}}$, indicating the poor reliability of submaximal tests to exhaustion.

Performance protocols in which athletes are asked to complete a fixed amount of work or distance in the shortest possible time are more reliable than protocols of indeterminate length (Bishop, 1997; Hickey et al., 1992; Jeukendrup et al., 1996; Palmer et al., 1995; Schabert et al., 1996), as well as more valid. In a study of elite male cyclists, Coyle et al. (1991) reported a correlation of $r = 0.93$ between time to completion (TTC) of a 40-km laboratory time-trial and actual 40-km time-trial performance. Likewise, Palmer et al. (1995) reported a correlation of $r = 0.98$ between TTC of 20-km and 40-km laboratory time-trials and actual road racing performance.

Remarkably, when fixed duration/workload protocols are quantified in terms of power output (instead of time to completion), correlations with cycling performance grow stronger. For instance, Palmer et al. (1996), observed a correlation of -0.999 between average power output (in watts, W) and both 20-km and 40-km cycling time-trial performance. Similarly, Balmer et al. (2000) reported a strong correlation ($r = -0.99$, $P < 0.001$) between peak power output (W) and 16.1-km time-trial performance.

To their detriment, however, fixed duration/workload protocols are inherently time-consuming. For example, a 40-km time-trial requires approximately 50 minutes to complete for an elite cyclist and up to 90 minutes to complete for a sub-elite cyclist.

Therefore, the use of fixed duration/workload protocols to accurately predict and/or track changes in actual cycling performance is both questionable and undesirable.

In an attempt to improve upon the reliability, validity, and practicality of previous cycling performance protocols, Heil et al. (2000) introduced the Scaling Derived Protocol (SDP). Utilizing principles of allometrics, the SDP was designed as an incremental test to volitional exhaustion based on the energy demand of uphill cycling as influenced by body mass. Preliminary results indicate SDP time-to-exhaustion (TTE, min) correlates extremely well with actual uphill time-trial performance ($r = 0.97$ to 0.98), as does relative peak power output (W/kg; $r = 0.92$ to 0.97). The SDP is easy to administer, less time-consuming than previous protocols (average TTE < 15 min), and requires only minimal (and affordable) equipment. Also, the design of the SDP conveniently allows it to double as a $\dot{V}O_{2MAX}$ test for cyclists when appropriate.

Given the high validity and sound theoretical basis of the SDP, the purpose of the present study was to determine the ability of the SDP to accurately predict and/or track changes in actual endurance cycling performance. Such a protocol would be of considerable value to cyclists and coaches as they attempt to maximize cycling performance. Also, the practicality and relative affordability of the SDP could ultimately lead to more effective training and youth talent identification programs for cycling. Therefore, the purpose of the present study was to determine the ability of the SDP to predict and/or track changes in uphill time-trial cycling performance.

Methods

Subjects. Eighteen cyclists from Montana State University and the local Bozeman community volunteered participation for the study. All subjects were informed of the nature of the investigation and written consent was obtained in accordance with the guidelines set forth by the Montana State University Human Subjects Committee. Three subjects resigned from the study due to schedule conflicts or lack of motivation; two more cyclists moved away from the area prior to completion of the study. Physical characteristics and cycling experience of the remaining subjects ($n = 13$) are presented in Table 1. In order to determine the ability of the SDP to predict and track uphill time-trial performance over time, each subject participated in at least two of three matched field and laboratory tests.

<INSERT TABLE 1>

Field Testing. The uphill time-trial course was located at the entrance to the Lewis and Clark Caverns State Park, approximately 50 miles west of Bozeman. The course was 3.0 miles long, with an average gradient of 8%. Starting elevation was 1301 meters (4,270 feet) above sea level, and ending (maximum) elevation was 1618 meters (5307 feet) above sea level. Subjects were provided with a standing start (bicycle and rider supported by the primary investigator). A minimum of four digital handheld stopwatches were synchronized prior to each time-trial; two stopwatches were

transported to the top of the course to record finishing time and two stopwatches remained at the bottom for starting purposes. Time-trial performance was recorded to the nearest second. Average time-trial speed was calculated by dividing the performance time by the total time-trial distance (5.0 km). Each uphill time-trial was separated by exactly ten weeks (May 10th, July 19th, September 27th, 2001).

Scaling Derived Protocol (SDP). Each uphill time-trial was followed within ten days by a laboratory-based SDP (a minimum of 48 hours separated the field and laboratory tests). Upon arrival at the laboratory, bicycle rear tire pressure was standardized at 100 p.s.i. using a track pump with tire gauge (Specialized, USA). Each subject's bicycle was fitted to a Computrainer™ stationary trainer (Computrainer™ Pro, Model 8001, Racermate Inc., Seattle WA., USA) and calibrated according to the manufacturer's recommended procedure (see Instrumentation). Subject age was recorded to the nearest year, subject height (barefoot) was measured to the nearest centimeter, and subject mass (with cycling clothes, minus shoes) was measured to the nearest 0.25 kilogram. Once anthropometric measurements were complete, subjects were permitted a subjectively adequate warm-up period (10-30 minutes).

The power output (in watts, W) for each stage of the SDP was based on research previously conducted in this laboratory. In brief review, Heil (1998) determined that the external power demand (W_D) of uphill cycling scales with body mass (M_B) to the +0.89 power (e.g. $W_D \propto M_B^{0.89}$). Thus, the relative energetic cost of uphill cycling at a given speed and grade is less for heavier cyclists than for lighter cyclists. Assuming that the net external power demand of uphill cycling is equivalent to a cyclist's metabolic power

supply (Heil, 1998), Heil et al. (2000) modified the standard formula for power (Power = [average acceleration * mass] * average speed) to reflect the scaling relationship between body mass and uphill power demand:

$$\text{Power} = [g * M_B^{0.89} * \sin\theta] * s$$

where “g” is the constant of gravitational acceleration (9.81 m/s/s), “ θ ” is the average inclination angle of the road surface, and “s” is the average forward ground speed of the cyclist.

Using this equation, the power required for each cyclist to ride up a 5° slope (θ) at 6.72 m/s (s) was calculated and designated as Stage 5 of the SDP. Stage 1 of the SDP was then calculated as 20% of the Stage 5 power output value, Stage 2 as 40%, Stage 3 as 60%, Stage 4 as 80%, Stage 5 as 100%, and each stage thereafter increased by 10% (see Appendix B for a complete outline of the first 14 stages for subjects weighing 40-100 kg). Due to wattage limitations imposed by the Computrainer™, it was necessary to approximate SDP power output to the nearest ± 10 W. End measures of the SDP included time-to-exhaustion (TTE, min), absolute maximum power output (W_{MAX} , W kg^{-1}), maximum power output relative to body mass (W_{MAX}/m_b), maximum power output relative to combined body/equipment mass (W_{MAX}/m_c), and maximum oxygen uptake ($\dot{V}O_{2MAX}$, ml/kg/min).

SDP Subject Procedure. The subjects were allowed to select their own pedal cadence throughout the first five stages of the protocol, with the stipulation that their chosen pedal cadence be held constant (± 2 rpm) within a given stage. When the subjects

reached Stage 6, however, the investigator fixed the cadence for the remainder of the test based upon the observed cadence at that moment. The subjects remained seated during the entire protocol and were verbally encouraged to continue until volitional exhaustion, or until the investigator noted a drop in cadence of ≥ 5 RPM for ≥ 5 seconds. Time to completion (e.g. time-to-exhaustion) of the SDP test was recorded to the nearest second.

Maximal power output (W_{MAX}) and maximal oxygen uptake ($\dot{V}O_{2MAX}$) were also determined during the SDP test. W_{MAX} was defined as the power output corresponding to the final completed stage of the SDP, plus a fraction of the power output maintained in the final incomplete stage (Kuipers et al., 1985):

$$W_{MAX} = (W_{com} + t/60) * \Delta W$$

where W_{com} is the power output of the final completed SDP stage, t is the amount of time (sec) completed in the final uncompleted stage, and ΔW is the power output of the final incomplete stage. Maximum oxygen consumption was calculated as the average of the three highest consecutive $\dot{V}O_2$ measures during the SDP. The measurement of $\dot{V}O_{2MAX}$ was considered successful if two of the following three criteria were met: 1) A maximal heart rate within 10 beats of each subject's age predicted maximum heart rate (e.g. $220 - \text{age}$); 2) A maximum respiratory exchange ratio of ≥ 1.10 before the last successful $\dot{V}O_2$ measurement; 3) A plateau of $\dot{V}O_2$ evidenced by a change ≤ 2.1 ml/kg/min with an increase in power output.

Instrumentation

Scaling Derived Protocol (SDP). For the laboratory-based SDP, each subject's bicycle was fitted to a Computrainer™ stationary trainer (Computrainer™ Pro, Model 8001, Racermate Inc., Seattle WA., USA) that supported the mass of the bicycle and rider at the rear wheel axle. An adjustable roller unit was used to apply resistance to the rear wheel. The resistance applied to the roller unit was, in turn, controlled by an electromagnetic "load generator" via a handlebar-mounted keypad. Real-time measures of power output (W) at the rear wheel, along with pedal cadence recorded by a crank arm sensor, were displayed on the keypad.

The following steps were required to calibrate the Computrainer™ in accordance with the guidelines established by the manufacturer: 1) adjust the trainer stand to fit each bicycle, 2) clean the rear tire of dust and debris, 3) warm-up the rear tire for several minutes, and 4) perform a "roll down calibration". The "roll down calibration" estimates the rolling resistance between the rear tire and the adjustable roller (which can vary depending on tire pressure, tire temperature, and the amount of pressure between the tire and roller) so that the total resistance applied to the rear wheel is as accurate as possible. The resistance applied to the rear wheel is independent of pedal cadence.

Oxygen Consumption. Oxygen consumption for each SDP protocol was measured by standard open-circuit spirometry using a two-way breathing valve. A SensorMedics 2900 metabolic cart (SensorMedics Corporation, Yorba Linda, CA., USA) was used to continuously monitor expired gases; $\dot{V}O_2$ was calculated over 20-second

intervals. Prior to testing, the gas analyzers were calibrated with primary gas standards of known concentrations (26% O₂, N₂ balance; 4% CO₂, 16% O₂, N₂ balance), and the SensorMedics' ventilatory measures were confirmed with a calibrated 3-liter syringe (Model D, SensorMedics Corporation, Yorba Linda, CA., USA). All information was processed via an IBM computer using ProTrac software (SensorMedics Corporation, Yorba Linda, CA., USA).

Heart Rate. Heart rate data during each test were measured with a Polar Accurex Plus telemetry-based heart rate monitor (Polar Electro Inc., Woodbury, NY., USA). Heart rate was averaged every five seconds and downloaded to an adjacent computer via the serial port interface provided by the manufacturer. Maximal heart rate was determined as the highest five-second average heart rate during the SDP test.

Statistical Analysis

Multiple Pearson product-moment correlation coefficients (r) were used to determine the relationship between changes in SDP performance and uphill time-trial performance. Changes were calculated between Trials 1-2, 2-3, 1-3 for all dependent variables. Phase II statistical analyses were performed using StatisticaTM computer software (version 5.5, Statsoft, Inc., Tulsa, OK). The level of significance was preset at $\alpha = 0.05$ for all tests, Phase I and II.

Results

A minimum of eleven subjects took part in each matched uphill time-trial and laboratory-based SDP (May, July, and September 2001). Relevant performance results are presented in Table 2. Eight subjects managed to complete all three testing bouts; the remainder of subjects ($n = 3$) completed at least two matched testing trials. Table 3 provides a list of relevant environmental conditions encountered during each uphill time-trial.

<INSERT TABLE 2, TABLE 3>

The correlations between average time-trial speed and SDP time-to-exhaustion were very high for all trials ($r = 0.85$ to 0.90), as were the correlations between average time-trial speed and W_{MAX}/m_c ($r = 0.83$ to 0.92). Significant correlations were also observed between average time-trial speed and W_{MAX}/m_b ($r = 0.75$ to 0.90) and relative $\dot{V}O_{2MAX}$ ($r = 0.63$ to 0.73). Table 4 contains zero-order correlations between matched uphill time-trial and SDP performance measurements.

<INSERT TABLE 4>

The correlation between average time-trial speed and SDP time-to-exhaustion varied from $r = 0.26$ to 0.87 , but the correlation between average time-trial speed and

W_{MAX}/m_c was consistently high ($r = 0.71$ to 0.90), as was the correlation between average time-trial speed and W_{MAX}/m_c ($r = 0.70$ to 0.90). Tables 5 contains zero-order correlations among inter-trial changes in uphill time-trial and SDP performance variables (Trials 1-2, 2-3, 1-3, 1-2-3, respectively). Scatterplots depicting the relationships between inter-trial change in average time-trial speed and W_{MAX}/m_c are provided in Figures 1-4.

<INSERT TABLE 5>

<INSERT FIGURE 1, FIGURE 2, FIGURE 3, FIGURE 4>

Discussion

This study demonstrated that a laboratory-based cycling protocol can be used to predict and/or track changes in uphill time-trial performance. In support of Heil et al. (2000), SDP TTE and W_{MAX}/m_c were highly correlated ($r = 0.85$ to 0.90 and $r = 0.83$ to 0.92) with average uphill time-trial speed for all three testing periods (May, July, and September 2001), as were moderate correlations for W_{MAX}/m_b ($r = 0.75$ to 0.90) and relative $\dot{V}O_{2MAX}$ ($r = 0.63$ to 0.73). Once again, these values compare favorably with those previously reported in the literature (Balmer et al., 2000; Bishop et al., 1998; Hawley and Noakes, 1992; Lindsay et al., 1996; Schabort et al., 2000).

However, the primary purpose of the present study was to determine the ability of the SDP to track *changes* in uphill time-trial performance. Change-score correlations between average time-trial speed and W_{MAX}/m_b and W_{MAX}/m_c were significant for all three testing periods ($r = 0.70-0.90$ and $r = 0.71-0.90$, respectively), explaining 50% to 80% of the variance of inter-trial changes in average time-trial speed. Notably, change-score correlations associated with Trial 1 uphill time-trial data (Trial 1-2, 1-3) were consistently lower than change-score correlations associated with Trials 2-3. This is likely due to the fact that several of the subjects rode the Trial 1 uphill time-trial "blind" (with no prior reconnaissance), resulting in inter-trial learning effects. Also, Trial 3 environmental conditions (wind speed in particular) likely had an affect on change-score correlations for Trials 1-3. Despite these circumstances, however, correlations for change-scores between Trials 1-2 and 1-3 were still relatively favorable, (though not as high as correlations for change-scores between Trials 2-3). Furthermore, absolute and relative measures of W_{MAX} were sensitive to both positive and negative changes (increases and decreases) in average uphill time-trial speed, as depicted in Figures 3-6.

In contrast, Lindsay et al. (1996) failed to note significant change-score correlations between W_{MAX}/m_b and flat 40-km time-trial performance before and after a four-week period of high-intensity interval training (despite significant improvements in both dependent variables). The reason for these results is likely due to the design of the incremental test employed by Lindsay and coworkers. The protocol commenced at a work rate equivalent to 3.33 W/kg body mass (m_b) for 150 seconds, then increased by 50 W for another 150 seconds. Following stage two, the exercise intensity was increased by

25 W every 150 seconds until volitional exhaustion – *regardless of body mass and/or the theoretical energy demands of flat 40-km time-trial cycling.*

Whereas the SDP was specifically designed to simulate the external power demand (W_D) of uphill cycling as influenced by body mass (e.g. $W_D \propto M_B^{0.89}$, Heil, 1998), the protocol used by Lindsay et al. failed to accurately simulate the power demand of flat 40-km cycling ($W_D \propto M_B^{0.32}$; Swain, 1994). It is not surprising, therefore, that changes in PPO failed to correlate with changes in 40-km time-trial performance.

Despite the high correlations observed in the present study between changes in SDP W_{MAX} and average time-trial speed, correlations between changes in SDP time-to-exhaustion and average time-trial speed were low to moderate ($r = 0.26$ to $.87$), explaining only 7% to 75% of the inter-trial variance. This discrepancy between two seemingly analogous measures of SDP performance can be explained by taking a closer look at the theoretical and structural design of the SDP.

The SDP was primarily designed to simulate the energy demand of uphill cycling as influenced by body mass. Stage 5 of the SDP is accordingly designated as the estimated power demand required for a person of a given body mass to propel a bicycle up a 8.7% (5°) incline at 6.72 m/s (15 MPH). This particular speed and grade were chosen to approximate a sub-lactate threshold power output in *moderately trained collegiate cyclists* (Heil et al, 2000).

At this point it is important to recognize a secondary purpose of the SDP: to serve as a valid and reliable $\dot{V}O_{2MAX}$ test for cyclists when appropriate. As such, the remaining SDP stages were designed to fit within the eight to twelve minute time period considered

ideal for the determination of maximal cardiopulmonary capacity (Buchfuhrer et al., 1983). Stage 1 was arbitrarily calculated as 20% of the Stage 5 value, Stage 2 as 40%, Stage 3 as 60%, etc. Stages 6 and above increase by 10% increments of Stage 5.

Therefore, it is easy to understand why TTE is not as sensitive to changes in uphill time-trial performance as W_{MAX}/m_c . Whereas W_{MAX}/m_c is theoretically derived to correlate highly with uphill time-trial performance, TTE is bound by the time limitations for the proper assessment of $\dot{V}O_{2MAX}$. Though unconfirmed, this trait is likely inherent to all PPO protocols designed with the secondary purpose to assess $\dot{V}O_{2MAX}$; measures of W_{MAX} will always correlate more strongly with performance than measures of TTE or TTC. A second factor potentially responsible for the low to moderate change-score correlations associated with TTE is the relatively lower reliability of TTE (when compared to W_{MAX} , Phase I).

There are several benefits of modeling the SDP after an uphill time-trial as opposed to a flat time-trial. In addition to significantly simplifying the underlying calculations of contributing factors to the overall energy demand of cycling (see Heil et al., 2000, Appendix), an uphill time-trial simulation may also be more relevant and valid for the prediction of overall professional cycling success.

Hills determine the outcome of a road race more than any other element. It is a basic function of time: even on circuit courses containing equal-length segments of positive and negative elevation gain, cyclists' overall time will be greater on the uphill (Kyle, 1988; Swain, 1997). Though larger cyclists may descend faster than smaller, climbing-proficient cyclists, they cannot make up the time lost going uphill (Swain,

1994). Additionally, the relative power-to-drag advantage of large cyclists on the flats (Swain, 1994) is effectively negated by the ability of smaller cyclists to remain tucked within the sheltering draft of the peloton (thus reducing their air resistance by as much as 40%, (McCole et al., 1990)). And once the road begins to climb again, the increased grade and slower speeds play conveniently to the talents of climbers. For these reasons, victors of the predominantly hilly grand tours (Tour de France, Giro d'Italia, and the Vuelta a España) tend to be smaller, climbing-proficient cyclists (Swain, 1994). Consequently, a laboratory protocol capable of predicting and/or tracking changes in uphill time-trial performance may also predict cycling success on a higher level.

Table 1. Subject Characteristics, Phase II (n = 13). Repeated measures reported as $\bar{x} \pm \text{SD}$.

Subject ID#	Trials Completed	Gender	Age (yrs)	Body Mass (kg)	Height (m)	Competition Level*
1	1,2,3	F	29	56.3 (0.9)	1.60	2
2	1,2	F	27	54.3 (0.4)	1.63	2
3	1,2,3	M	29	74.5 (1.9)	1.65	2
4	1,2,3	M	29	69.0 (1.0)	1.75	1
5	1,3	M	24	70.3 (1.8)	1.76	3
6	1,2,3	M	48	77.0 (0.1)	1.78	3
7	1,2	M	29	80.0 (0.7)	1.89	1
8	1,2	M	37	83.3 (2.1)	1.78	1
9	1,2,3	M	44	81.8 (0.6)	1.85	1
10	1,2,3	M	24	81.0 (2.8)	1.78	3
11	1,3	M	33	78.8 (0.5)	1.88	1
12	1,2,3	M	53	73.8 (0.9)	1.78	1
13	2,3	M	36	81.0 (0.7)	1.88	1
Ave (SD)			34 (9.2)	73.8 (9.3)	1.77 (0.09)	

*Competition Level is reflective of the classification systems used by the United States Cycling Federation (USCF) and the National Collegiate Cycling Association (NCCA): 1 = USCF Category 1-2 and/or NCCA Category A; 2 = USCF Category 3 and/or NCCA Category B; 3 = USCF Category 4 and/or NCCA C-D.

Table 2. Phase II uphill time-trial and laboratory-based SDP results for all subjects. All values reported Mean $\pm$ SD (Range).

	Trial 1 (n=12)	Trial 2 (n=11)	Trial 3 (n=11)
1 TT Speed (m/s)	4.5 $\pm$ 0.5 (3.6-5.3)	4.7 $\pm$ 0.5 (3.7-5.6)	4.7 $\pm$ 0.5 (3.6-5.3)
2 SDP TTE (min)	11.3 $\pm$ 1.2 (8.3-13.0)	11.8 $\pm$ 1.3 (9.0-13.7)	11.6 $\pm$ 1.2 (8.3-13.0)
3 Absolute $\text{VO}_{2\text{MAX}}$ (l/min)	4.75 $\pm$ 0.8 (3.1-5.5)	4.8 $\pm$ 0.8 (3.0-5.5)	4.8 $\pm$ 0.7 (3.1-5.7)
4 Relative $\text{VO}_{2\text{MAX}}$ (ml/kg/min)	64.2 $\pm$ 5.19 (53.8-74.0)	65.4 $\pm$ 6.4 (55.0-80.6)	63.9 $\pm$ 6.9 (54.8-78.6)
5 W_{MAX} (W)	351.3 $\pm$ 57.4 (230-410)	363.3 $\pm$ 57.6 (250-428)	362.6 $\pm$ 48.0 (230-410)
6 W_{MAX}/m_b (W/kg)	4.8 $\pm$ 0.3 (4.0-5.2)	4.9 $\pm$ 0.3 (4.5-5.6)	4.9 $\pm$ 0.3 (4.1-5.3)
7 W_{MAX}/m_c (W/kg)	4.2 $\pm$ 0.3 (3.4-4.7)	4.3 $\pm$ 0.4 (3.8-4.9)	4.3 $\pm$ 0.3 (3.4-4.6)

TTT Speed = average uphill time-trial speed; SDP TTE = laboratory protocol time-to-exhaustion; $\text{VO}_{2\text{MAX}}$ = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Table 3. Air temperature, relative humidity, and wind ranges encountered during the three uphill time-trials.

	Air Temperature	Relative Humidity	Wind Speed Ranges*	
			Minimum	Maximum
Time-trial #1	68° F	31.0%	0-4 MPH	7-15 MPH
Time-trial #2	75° F	26.0%	0-6 MPH	10-14 MPH
Time-trial #3	72° F	12.5%	0-5 MPH	15-20 MPH

*Minimum wind speeds were encountered during the first sheltered two-thirds of the time trial course.

Maximum wind speeds were encountered at the more exposed summit-finish of the time-trial course.

Table 4. Correlations between average TT speed (m/s) and SDP performance variables.

	Trial 1	Trial 2	Trial 3
1 SDP TTE (min)	0.86*	0.90*	0.85*
2 Absolute VO _{2MAX} (l/min)	0.55	0.70*	0.80*
3 Relative VO _{2MAX} (ml/kg/min)	0.73*	0.75*	0.63*
4 W _{MAX} (W)	0.53	0.68*	0.76*
5 W _{MAX} /m _b (W/kg)	0.75*	0.90*	0.77*
6 W _{MAX} /m _c (W/kg)	0.84*	0.92*	0.83*

*Values differ significantly from zero, $P < 0.05$. TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Table 5. Correlations between inter-trial changes in average TT speed (m/s) and SDP performance variables.

	Trials 1-2	Trials 2-3	Trials 1-3	Trials 1-2-3
1 SDP TTE (min)	0.57	0.87*	0.26	0.54*
2 Absolute VO _{2MAX} (l/min)	0.23	0.56	0.60	0.54*
3 Relative VO _{2MAX} (ml/kg/min)	0.47	0.72*	0.66	0.67*
4 W _{MAX} (W)	0.70*	0.85*	0.48	0.63*
5 W _{MAX} /m _b (W/kg)	0.73*	0.90*	0.71*	0.75*
6 W _{MAX} /m _c (W/kg)	0.74*	0.90*	0.70*	0.75*

*Values differ significantly from zero, $P < 0.05$. TTE = laboratory protocol time-to-exhaustion; VO_{2MAX} = maximum oxygen consumption; W_{MAX} = SDP maximum power output; m_b = body mass (kilograms); m_c = combined mass of cyclist (m_b) and cycling equipment (kilograms).

Figure 3. Scatterplot depicts the relationship between Trial 1 and Trial 2 changes (T2-T1) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.001 + 0.522 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.55$.

Figure 4. Scatterplot depicts the relationship between Trial 2 and Trial 3 changes (T3-T2) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.066 + 0.928 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.81$.

Figure 5. Scatterplot depicts the relationship between Trial 1 and Trial 3 changes (T3-T1) in uphill average time-trial speed (m/s) and W_{MAX}/m_c (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.066 + 0.928 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.81$.

Figure 5. Scatterplot depicts relationship between changes for all trials (1-2, 2-3, 1-3) in uphill average time-trial speed (m/s) and W_{MAX} (W/kg). Solid line is least-squares derived linear regression: speed (m/s) = $0.005 + 0.727 \times W_{MAX}/m_c$ (W/kg), $r^2 = 0.56$.

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