Redefining Road Cycling Performance From Field Determinations of Power Output

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REDEFINING ROAD CYCLING PERFORMANCE
FROM FIELD DETERMINATIONS OF POWER OUTPUT

by

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Abstract

In the laboratory, cycling has been a common model for studying the physiological responses to physical activity due to its popularity as a recreational activity\(^1\), the ability to precisely quantify the exercise stimulus through measures of power and work, and the diverse physiological demands imposed by competitive cycling events. To date, this research effort has been limited primarily to steady state or graded exercise protocols in controlled laboratory environments. Recent technological advances, however, have resulted in the development of hub and crank based power meters that can be fitted to standard road bicycles, allowing power and work to be monitored in the field. Thus, in the same way that cycling has been an important model for laboratory research, the intent of this present research has been to extend this model to the field with an initial emphasis on redefining road cycling performance. As a first step we demonstrated that cycle mounted power meters were accurate and precise under dynamic load against both physiological and mechanical references. We then focused on examining the demands of competitive cycling in female and male professional cyclists, observing a complex, seemingly stochastic pattern of power output during competition that encompassed a much broader power and metabolic spectrum than previously characterized by laboratory simulations or

\(^1\) According to the National Association of Sporting Good Retailers, cycling is second only to walking as the most popular recreational activity in the United States.
field measures of heart rate. Because this pattern of power output is a result of a cyclist's physiological capacity to produce power and physical factors that impede forward motion, we validated a protocol for isolating aerodynamic drag and rolling resistance from field measures of power and speed, showing that these variables could be measured to a degree of accuracy comparable to more costly, complicated, and less specific methods. Finally, using this technique in combination with physiological measures gathered in the laboratory, we were able to dissect the physical and physiological attributes determining uphill and level time trial performance in the field.
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CHAPTER I: GENERAL INTRODUCTION

Historically, the ability to measure external power and work during exercise has been limited to cycle ergometry. As a result, cycling as a mode of exercise has played a fundamental and extensive role in basic and applied exercise science research. Because of the diverse and extreme demands of competitive cycling, ranging from sprint to ultra-endurance events, this research has been driven in large part by attempts at understanding and optimizing performance in novice to professional cyclists. With the extensive use of cycling in rehabilitative settings and the enormous popularity of cycling as a recreational activity, the knowledge gained by studying performance in these athletes has also had direct application beyond the competitive arena.

Unfortunately, in the laboratory, where power can be accurately measured, most studies are based on graded or steady state exercise protocols. At the same time, in the field, studies generally focus only on the individual time trial and exercise intensity, which is not related to speed due to variations in terrain, is almost always measured indirectly with heart rate. This is problematic, since most sports and physical activities are non-steady state events and evidence exists that the heart rate response can dissociate from power output and other physiological responses during intermittent exercise (3, 9). Consequently, despite extensive knowledge about cycling physiology, we know very little about the physical demands of road cycling nor do we completely understand the acute and/or chronic adaptations associated with training and competition. This leaves important questions about the most optimal testing, training, and racing strategies unanswered (1).
Recently, two products, the Schoberer Resistance Meter (SRM™, Julich Germany) and CycleOps Power Tap® (Power Tap, Madison, WI), that can measure power output on standard racing bicycles have become commercially available. The SRM is a modified bicycle crank with 4 strain gauges embedded in a plate between the two front chain rings. Torque and angular velocity are measured within the plate and inductively transmitted at 200 Hz to a receiver that relays this data to an onboard computer that stores up to 10 hours of data in 1 to 2 second increments. The Power Tap is a modified rear hub with 4 strain gauges evenly distributed within an aluminum tube connected to the rear cogset (torque tube). Torque and angular velocity are measured within the torque tube and transmitted at 60 hz via radio telemetry to a receiver that relays data to a computer that stores up to 7 hours of data in 1 to 3 second increments. In addition to their ability to measure power, both units can also monitor heart rate via radio telemetry and also record time, distance, speed, and pedaling cadence. The Power Tap and SRM add a minimal amount of weight (200 to 300 grams) to the bicycle compared to standard cranksets or hubs and can be mounted to any standard racing bicycle.

Despite the potential of directly quantifying the stress associated with exercise by measuring power output in the field during actual training or competitive events, these power meters are not widely used in research settings. This may be due, in part, to the limited literature describing the reliability and validity of these devices. At present, only the SRM has been validated against other laboratory-based ergometers or a mechanical reference (43). Due to the cost of the SRM (≈ $2,500.00) and Power Tap (≈ $700.00), compared to heart rate monitoring, the widespread use of this
equipment may also be cost prohibitive. To justify this cost and to assure scientifically rigorous data, extensive work is needed to determine the validity and reliability of this equipment. The potential accuracy and reliability of these cycle mounted power meters could make measuring power in the field scientifically feasible, making cycling an important model for both laboratory and field research.

Assuming the reliability and validity of these cycle mounted power meters, an important first step would be to re-examine the actual demands of competitive road cycling. Currently, our understanding of these demands is based almost entirely on heart rate monitoring. While there is a significant and linear relationship between heart rate and power output in the laboratory during graded exercise, whether this relationship remains in different settings is controversial (42). In fact, there are a number of factors that can dissociate the relationship between heart rate and power output. They include, cardiovascular drift associated with changes in peripheral blood flow and dehydration during prolonged exercise in the heat (13, 47, 48), acute changes in altitude (35, 50), changes in circulating catecholamines (51), the psychological state of the individual (10, 46), variations in fitness (23), and intensified training and/or overreaching (7, 49). In addition, during non-steady state exercise conditions, changes in the pattern of power output, especially during high intensity intermittent exercise, can drastically affect the heart rate response at the same average power output (3, 9, 28, 41). Finally, heart rate as an intensity measure is fixed to a physiological minimum and maximum and may not respond quickly enough to sudden changes in power output (33, 42). As a result, it is unlikely that heart rate reflects the true metabolic or physical demands of competitive cycling (9,
Thus, the average power, energy expenditure, and distribution of power output during road cycling events may be quite different than previously reported (21, 31, 32).

While an accurate description of the power outputs produced by cyclists during competition is critical to understanding performance, a cyclist’s velocity is not only determined by his or her ability to produce power, but a function of power and all of the physical forces that resist forward motion (34, 37). Accordingly, performance in cycling would be optimized by maximizing a cyclist’s external power output while also minimizing the total resistance faced by that cyclist. More importantly, without a way to measure these resistive demands, knowing a cyclist’s power alone may not be enough to predict performance.

The primary forces resisting the forward motion of a cyclist are gravitational, rolling, and aerodynamic resistance (34). Of these factors, a single technique for assessing aerodynamic drag or rolling resistance on a broad scale has yet to be adopted (11, 19, 20, 25). In addition, individual measures of aerodynamic and rolling resistance are not common in studies evaluating cycling performance (11, 12, 18-20, 25, 26, 34, 38, 45). Rather, these measures are generally assumed from previously established references or from estimates of projected frontal area, despite the large variability in aerodynamic resistance between different individuals, body positions, and equipment (5, 37, 39, 40). Thus, an accessible and accurate technique to assess an individual’s true aerodynamic and rolling resistance is needed. A potential technique for the quantification of aerodynamic drag may be the analysis of the power versus speed relationship of an individual cyclist riding at a constant speed on level ground.
Whether, however, the current generation of cycle mounted power meters can accurately measure and distinguish this variable within and between subjects remains unknown.

A cyclist’s ability to produce and sustain power is highly dependent upon physiological characteristics like their maximal aerobic capacity (\(\text{VO}_2\) max), the lactate threshold (LT), and economy (Econ) (14-17). In the laboratory where resistive forces are controlled or minimized, these physiological factors have been successfully used to predict simulated time trial performance (6, 8, 14, 16, 17, 27, 29, 30, 36, 44). In the field, however, measures of a cyclist’s ability to supply power do not always predict performance even in the simplified arena of time trial racing (2, 24), especially in homogeneous groups. With the possibility of accurately measuring the resistive forces associated with cycling in conjunction with physiological characteristics known to be important to performance, the possibility now exists to accurately predict performance using both physical and physiological factors.

As a result of the research possibilities that currently exist with the use of cycle mounted power meters and the many unanswered questions about their use in this capacity we have created a number of research goals. First, we quantified the validity and reliability of the Power Tap device, with respect to a first principles external dynamometer, and the metabolic response associated with a graded exercise stress test on a standard laboratory ergometer versus a bicycle mounted with a Power Tap. Next we sought to directly compare how measures of heart rate and power output describe the distribution of exercise intensity and energy expenditure during a six-day professional stage race in professional cyclists. Thereafter, we assessed
whether the Power Tap and SRM power meters could be used to accurately measure aerodynamic and rolling resistance. Finally, we quantified physical factors that contribute to resistance during cycling (i.e., aerodynamics, rolling resistance, and body weight) in conjunction with physiological determinants of endurance performance (i.e., VO2 max, lactate threshold, and economy) in well to highly trained male cyclists to examine the relationship between these physiological and physical measures with actual field measures of performance time and power output during an uphill and level time trial.

In the future, we hope to utilize our knowledge of the competitive demands of road cycling competitions along with the physical forces that resist movement in cycling to accurately simulate field performances in the laboratory on a unique treadmill capable of replicating the course profiles and physical resistance associated with outdoor cycling.
References


CHAPTER II: THE VALIDITY AND RELIABILITY OF A HUB-MOUNTED POWER METER FOR CYCLING

Abstract

Purpose: To determine the efficacy of the Power Tap (PT) cycle mounted power meter as a laboratory-based research tool, we made mechanical and metabolic assessments to reference the PT against a first principles dynamometer (mechanical), and Lode electromagnetic ergometer (metabolic). Methods: During the mechanical trials, 20 PT units were compared to the dynamometer from 100W to 500W for an inter-unit analysis, and a single PT was referenced 20 times for an intra-unit analysis. In the metabolic trials the $\dot{V}O_2$-power relationships from 14 male cyclists were compared while the subjects performed graded exercise tests on 1) their own bicycles fitted with a PT, or 2) the Lode ergometer. Simple regressions were fit to the mechanical (Power-power W.W$^{-1}$) and metabolic ($\dot{V}O_2$-power, L.W$^{-1}$) data. Mean results for the mechanical (PT-Dynamometer) regressions were: slope = 0.969 W.W$^{-1}$, intercept = -3.86 W, and $r = 0.9998$. During the mechanical trials a scientific model SRM power meter was tested concurrent to the PT and was not different in terms of slope, but was different in terms of intercept ($P < 0.05$). Variability in the regressions for the PT was slight, and not different within vs. between units, or with respect the SRM ($P > 0.05$). The slopes from the PT and Lode $\dot{V}O_2$-power regressions were identical (0.012 L.W$^{-1}$), while the PT intercept (0.522 L) was greater than that of the Lode (0.410L). Subjects attained similar values for oxygen consumption and power output at peak exercise for the Lode and PT ($P > 0.05$). Conclusion: These results
indicate the Power Tap to be a valid and reliable measure of cycling power, and suitable for graded exercise stress testing.

**Introduction**

The recent development of cycle-mounted power meters (CMPM) has provided a means of directly quantifying the exercise stress applied to an athlete, while riding his or her own bicycle, either in the field or laboratory. Such a device can be used to describe the training and racing loads experienced by elite athletes (Martin *et al.* 2001) and as such, provide a direct measure of exercise stress during an activity in which that stress has most often been estimated from measures of physiological strain (Lucia *et al.* 1999; Padilla *et al.* 1999, 2000 & 2001; Palmer *et al.* 1994). Furthermore, by offering this direct measure, CMPMs have presented a means of assessing the stress-response relationship in an activity that exhibits a remarkably variable exercise demand (Martin *et al.* 2001).

At this time the application of cycle-mounted power meters toward scientific objectives has been fairly limited, but the potential for such application remains substantial. It is likely that, in part, a lack of literature describing the quality of these devices has precipitated their exclusion from many applicable investigations. Currently only one commercially available power meter, the SRM™, has been validated against other popular laboratory-based ergometers, or a mechanical reference (Paton *et al.* 2001). A hub mounted power meter (Power Tap™, Graber Products, Madison WI) has recently become available as a commercial alternative to the SRM device. The Power Tap offers a more cost effective means of power
measurement, but has not yet been validated for scientific use, or for non-scientific applications requiring a fine measure of power.

This investigation sought to quantify the validity and reliability of the Power Tap device, with respect to a first principles external dynamometer, and the characteristic metabolic responses of a graded exercise stress test.

**Methods**

The validity and reliability of a commercially available rear-hub based power meter (Power Tap™) were assessed here by means of two independent protocols, one mechanical, and one metabolic. The mechanical validation involved both intra-unit and inter-unit comparisons between the Power Tap and a first principles mechanical reference. The metabolic validation involved a repeated measures comparison of the $\dot{V}O_2$-power relationships exhibited by well-trained cyclists during graded exercise stress tests. These tests were performed either on the subject’s own racing bicycle equipped with a Power Tap and mounted to a stationary trainer, or on a laboratory grade electromagnetically braked ergometer.

The testing protocol remained constant for all trials comprising the mechanical validation, and involved an incremental increase in the power applied to the bottom bracket of a standard road-racing bicycle (Red Zinger model, Morgul Bismark, Niwot, CO). This power output was achieved by coupling an external dynamometer to the bottom bracket of the bicycle, and applying a resistance to the rear wheel via an electromagnetically braked cycle trainer (“Pro basic” model Computrainer, RacerMate Inc., Seattle, WA). The motor of the dynamometer
operates at a rotational velocity (cadence, rpm) specified by the technician, and simply matches the resistive torque acting at the bottom bracket. The Computrainer provided this resistance, and was therefore used to increase the power acting through the entire system. This arrangement allowed for a comparison of the concurrent power measures obtained from 1) the external dynamometer, and 2) the Power Tap unit being tested. See figure 1-1 for a visual description of the system.

Within the drive-train assembly, a scientific model SRM was also mounted to aid interpretation of any differences observed between the Power Tap and Dynamometer.

During each test, the resistance provided by the Computrainer was increased to elicit power outputs that ranged from 100 to 500 Watts at 50 W increments, and each increment was maintained for a time interval of 1 minute. This range was selected to represent the workload limits reached by our population of elite cyclists during the graded protocol described below, and is similar to ranges reported elsewhere (Balmer et al. 2000). The cadence of the external dynamometer was held constant (100 rpm) across and during all tests.

The external dynamometer utilized here was loaned by the United States Olympic Committee and has been described previously (Kyle. 1992). Simply stated, the dynamometer mechanism is a torque motor capable of matching an applied resistance at a designated cadence. As mentioned, the cadence is under the control of the experimenter, and was constant across all tests. An autopsy scale (Chatillon 1315ADD model, Ametek instruments, Largo, FL) was attached via synthetic cord to a lever arm that extended from the dynamometer body. In this way the torque applied
Figure 1-1. Picture of dynamometer arrangement indicating various components: A – Chatillon autopsy scale, B – Moment arm linking scale to torque motor, C – Torque motor, D – Drive shaft and bottom bracket coupling mechanism, E – SRM crankset, F – Power Tap hub, G – Computrainer electromagnetic resistance unit.
by the dynamometer was transferred to the scale, where it could be read in terms of a mass equivalent. To derive measures of power (W) from cadence (rpm) and resistive load (kg), several physical conversion factors were required and are described in equations 1 through 4. Prior to data collection, the accuracy of the Chatillon scale was verified by suspending a series of known masses across the range apparent during pilot testing.

The power applied to the bottom bracket of the bicycle was derived as follows:

\[
\text{Power (W)} = \text{Torque (N.m)} \times \text{Angular velocity (rads.s}^{-1})
\]

(1)

Where:

a) \[
\text{Torque} = \text{Force (N)} \times r (0.4058m) = \text{Mass (kg)} \times A_g (9.81m.s}^{-2}) \times 0.4058
\]

(2)

b) \[
\text{Angular velocity} = [2 \times \pi \times \text{cadence (100 rpm)}] \div [\text{Time (60 s)}]
\]

(3)

Substituting:

\[
\text{Power} = [(\text{Mass} \times 9.81 \times 0.4058) \times (2 \times \pi \times 100)] \div [\text{Time (60 s)}]
\]

Simplified for this dynamometer:

\[
\text{Power} = 41.69 \times \text{Mass}
\]

(4)

To assess the intra-unit variability of the Power Tap, data were obtained from a single unit tested 20 separate times. For between-unit comparisons, data were obtained from 20 different units each tested twice.

*Metabolic validation:*

To determine the potential of the Power Tap as a laboratory-based instrument, 14 competitive male cyclists (professional & USCF category 1-2 amateur) each
performed a total of four graded exercise stress tests. Prior to involvement all subjects were required to complete a comprehensive medical questionnaire and sign a statement of informed consent, both of which were approved by the Human Research Committee at the University of Colorado at Boulder. Two of the graded exercise stress tests were performed on the subject’s own bicycles fitted with a Power Tap, and the other two on an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, the Netherlands), adjusted to replicate the subject’s position on their own bicycle. Test order was alternated between the Power Tap and the Lode, with the initial test condition being randomly selected. When subjects performed on their own bicycles, the resistance was applied via the same Computrainer as was used during the mechanical validation. All tests involved a 4 minute × 30 Watt stepped submaximal protocol which was terminated when the subject achieved a rating of perceived exertion ≥ 15 (Borg scale). The subject was then allowed to rest for 8 minutes before continuing to volitional exhaustion at 1 minute × 30 Watt increments.

Assessments of indirect calorimetry were made from measures of expired gas concentration and inspiratory ventilation. Expired gases were fed into a 5 L mixing chamber and sampled continuously by a Perkins-Elmer 1100 mass spectrometer (Boston, MA). Inspiratory ventilation was measured with a Hans-Rudolph pneumotachometer and differential pressure transducer (model MP45-14, Validyne engineering, Northridge, CA). The analog signals from both the gas analyzer and pressure transducer were conditioned externally (amplified and filtered - model MC1-3-871, Validyne engineering, Northridge, CA), before being interfaced with a Dell GX1 personal computer via analog-digital conversion and TrueMax 2400 software
(ParvoMedics, Sandy, UT). Prior to and directly following each testing session this system was calibrated with known gas fractions and volumes. Data were collected continuously and analyzed as discrete 30-second averages. Only data for the final 2 minutes of each stage were used to arrive at the oxygen cost of the workload during the submaximal portion. Peak oxygen consumption was defined as the highest oxygen consumption averaged over any 30-second interval of the maximal portion of the protocol.

Statistical Analyses:

Linear regression analyses were applied to data obtained from the mechanical validation (Power Tap vs. Dynamometer and SRM vs. Dynamometer). From these regressions, values for both the slopes and intercepts from the inter-unit trials were assessed for differences between trials one and two with a paired Student’s t-test. Unpaired Student’s t-tests were used to compare the intra-unit trials and inter-unit trials in terms of slope and intercept, and also to compare the Power Tap vs. Dynamometer regression results to the SRM vs. Dynamometer results. F-tests were used to compare the variances of the slope and intercept measures for the intra-unit trials, inter-unit trials, and SRM.

Linear regressions were also applied to the $\dot{V}O_2$-power relationships obtained during the metabolic validation. The mean slopes and intercepts of the two submaximal conditions (Power Tap vs. Lode) were each assessed by a $2 \times 2$ (Ergometer $\times$ Time) repeated measures ANOVA. $2 \times 2$ (Ergometer $\times$ Time)
repeated measures ANOVAs were also used to assess values obtained at maximal exercise.

Results

Mechanical Validation:

Regression results for each trial from the intra-unit comparisons, and each unit from the inter-unit comparisons, are presented in table 1-1. As no differences were found between the first and second trials performed on each of twenty different Power Tap units during the inter-unit comparison (Table 1-1: slope comparison $P = 0.658$, intercept comparison $P = 0.794$) the two trials were averaged (Table 1-2). In this way the variability apparent in the slope and intercept measures could be compared between the inter-unit and intra-unit assessments on equal terms of $n$.

The relationships between power measured by the Dynamometer ($X$) and Power Tap ($Y$) were strongly linear. This is confirmed by the mean coefficients of determination found for both the intra-unit ($r^2 = 0.9999 \pm 0.0002$) and inter-unit ($r^2 = 0.9997 \pm 0.0007$) comparisons. The mean regression equations for both the intra-unit and inter-unit comparisons indicate slight but systematic differences between the Power-Tap and Dynamometer measures. These differences were evident in both the mean slopes of the relationships (mean intra-unit slope = 0.969 W.W$^{-1}$, mean inter-unit slope = 0.963 W.W$^{-1}$), and their intercepts (mean intra-unit intercept = -3.86 W, mean inter-unit intercept = -6.55 W). See figure 1-2 for a graphical representation of these results. Of these values only the mean intercepts were different between the intra-unit and inter-unit trials ($P = 0.0004$).
Table 1-1. Values for the slopes (W.W'), intercepts (W) and coefficients of determination (r^2) for each of the twenty trials conducted during the intra-unit comparisons, and each of the forty trials performed on twenty Power Tap units during the inter-unit comparisons.
<table>
<thead>
<tr>
<th>Trial</th>
<th>Intra-unit results Power Tap vs. Dynamometer</th>
<th>Power Tap</th>
<th>Inter-unit results Power Tap vs. Dynamometer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>Intercept</td>
<td>$r^2$</td>
</tr>
<tr>
<td>1</td>
<td>0.986</td>
<td>-7.7</td>
<td>0.9998</td>
</tr>
<tr>
<td>2</td>
<td>0.965</td>
<td>-3.5</td>
<td>0.9999</td>
</tr>
<tr>
<td>3</td>
<td>0.966</td>
<td>-1.5</td>
<td>0.9998</td>
</tr>
<tr>
<td>4</td>
<td>0.977</td>
<td>-6.1</td>
<td>0.9999</td>
</tr>
<tr>
<td>5</td>
<td>0.971</td>
<td>-4.4</td>
<td>0.9999</td>
</tr>
<tr>
<td>6</td>
<td>0.964</td>
<td>-3.2</td>
<td>0.9999</td>
</tr>
<tr>
<td>7</td>
<td>0.975</td>
<td>-5.6</td>
<td>1.0000</td>
</tr>
<tr>
<td>8</td>
<td>0.974</td>
<td>-6.1</td>
<td>0.9998</td>
</tr>
<tr>
<td>9</td>
<td>0.965</td>
<td>-3.3</td>
<td>1.0000</td>
</tr>
<tr>
<td>10</td>
<td>0.960</td>
<td>-1.6</td>
<td>0.9998</td>
</tr>
<tr>
<td>11</td>
<td>0.979</td>
<td>-6.0</td>
<td>0.9999</td>
</tr>
<tr>
<td>12</td>
<td>0.952</td>
<td>-0.4</td>
<td>0.9996</td>
</tr>
<tr>
<td>13</td>
<td>0.959</td>
<td>-2.7</td>
<td>1.0000</td>
</tr>
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<td>0.977</td>
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<td>0.9999</td>
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<td>1.0000</td>
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<td>16</td>
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<td>0.9998</td>
</tr>
<tr>
<td>17</td>
<td>0.977</td>
<td>-3.5</td>
<td>0.9998</td>
</tr>
<tr>
<td>18</td>
<td>0.965</td>
<td>-3.1</td>
<td>0.9998</td>
</tr>
<tr>
<td>19</td>
<td>0.963</td>
<td>-0.7</td>
<td>0.9999</td>
</tr>
<tr>
<td>20</td>
<td>0.956</td>
<td>-3.6</td>
<td>0.9999</td>
</tr>
<tr>
<td>Mean</td>
<td>0.969</td>
<td>-3.9</td>
<td>0.9999</td>
</tr>
<tr>
<td>SD</td>
<td>0.009</td>
<td>2.0</td>
<td>0.0001</td>
</tr>
<tr>
<td>Range</td>
<td>0.034</td>
<td>7.3</td>
<td>0.0004</td>
</tr>
</tbody>
</table>
Table 1-2. Average values for the slopes \( W.W^{-1} \), intercepts \( W \) and coefficients of determination \( r^2 \) for each Power Tap unit tested during the inter-unit trials.
<table>
<thead>
<tr>
<th>Power Tap Unit #</th>
<th>Mean Inter-unit results Power Tap vs. Dynamometer</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slope</td>
<td>Intercept</td>
<td>$r^2$</td>
</tr>
<tr>
<td>1</td>
<td>0.981</td>
<td>-7.3999</td>
<td>0.9998</td>
</tr>
<tr>
<td>2</td>
<td>0.976</td>
<td>-8.5347</td>
<td>0.9998</td>
</tr>
<tr>
<td>3</td>
<td>0.973</td>
<td>-3.7243</td>
<td>0.9998</td>
</tr>
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<td>4</td>
<td>0.969</td>
<td>-6.6743</td>
<td>0.9997</td>
</tr>
<tr>
<td>5</td>
<td>0.953</td>
<td>-4.5672</td>
<td>0.9998</td>
</tr>
<tr>
<td>6</td>
<td>0.958</td>
<td>-4.4063</td>
<td>0.9996</td>
</tr>
<tr>
<td>7</td>
<td>0.967</td>
<td>-8.3933</td>
<td>0.9999</td>
</tr>
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<td>8</td>
<td>0.968</td>
<td>-7.0039</td>
<td>0.9999</td>
</tr>
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<td>0.963</td>
<td>-5.4621</td>
<td>0.9999</td>
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<td>10</td>
<td>0.954</td>
<td>-8.2178</td>
<td>0.9999</td>
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<tr>
<td>11</td>
<td>0.975</td>
<td>-11.3405</td>
<td>0.9999</td>
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<td>12</td>
<td>0.939</td>
<td>-3.6455</td>
<td>0.9996</td>
</tr>
<tr>
<td>13</td>
<td>0.945</td>
<td>-1.8051</td>
<td>0.9967</td>
</tr>
<tr>
<td>14</td>
<td>0.957</td>
<td>-7.4045</td>
<td>0.9998</td>
</tr>
<tr>
<td>15</td>
<td>0.974</td>
<td>-9.1385</td>
<td>0.9998</td>
</tr>
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<td>16</td>
<td>0.948</td>
<td>-6.6136</td>
<td>0.9999</td>
</tr>
<tr>
<td>17</td>
<td>0.971</td>
<td>-9.2313</td>
<td>0.9999</td>
</tr>
<tr>
<td>18</td>
<td>0.964</td>
<td>-5.5597</td>
<td>0.9998</td>
</tr>
<tr>
<td>19</td>
<td>0.961</td>
<td>-4.063</td>
<td>0.9999</td>
</tr>
<tr>
<td>20</td>
<td>0.957</td>
<td>-7.9043</td>
<td>0.9999</td>
</tr>
<tr>
<td>Mean</td>
<td>0.963</td>
<td>-6.55</td>
<td>0.9997</td>
</tr>
<tr>
<td>SD</td>
<td>0.0112</td>
<td>2.36</td>
<td>0.0007</td>
</tr>
<tr>
<td>Range</td>
<td>0.0414</td>
<td>9.5354</td>
<td>0.0032</td>
</tr>
</tbody>
</table>
Figure 1-2. Mean regressions for intra-unit comparisons (♦), and inter-unit comparisons (□) of Power Tap measured power (dependent) and Dynamometer measured power (independent).
Power Tap power (W) = 26

Dynamometer power (W) = 100

Mean intra-unit regression: $y = 0.969x - 3.86$
Mean inter-unit regression: $y = 0.963x - 6.55$
Line of Identity
Regression variability: The variability of the intercept measure was similar for the intra-unit (SD = 2.0W) and inter-unit (SD = 2.37 W) comparisons, and so too was the variability of the slope values from the intra-unit (SD = 0.009) and inter-unit trials (SD = 0.0112) – Detailed data are presented in tables 1-1 & 1-2. To compare these measures of variability for statistical difference, F-tests were carried out and revealed that the intra-unit variance was not different to the inter-unit variance, either in terms of the slope ($P = 0.254$), or intercept ($P = 0.474$).

Metabolic Validation: Mean regression and correlation results for the relationship between rate of oxygen consumption and power output, at submaximal workloads, are presented in table 1-3. A main effect for ergometer was observed (Power Tap vs. Lode) at zero-load pedaling (intercept), while no differences were observed in either the regression slopes or coefficients of determination – Figure 1-3.

At maximal exercise there was no main effect for exercise condition (Lode vs. Power Tap) either in terms of the physiological variables, or measures of power output achieved. A main effect was observed for trial, indicating a potential learning effect (Table 1-4).
Table 1-3. Regression slopes (Slope, L.min⁻¹.W⁻¹), intercepts (Intercept, L.min⁻¹), and associated coefficients of determination (r²) from the oxygen consumption to power relationships found when subjects were tested with the Power Tap or Lode. All values are presented as means ± standard deviation. * P < 0.05.
<table>
<thead>
<tr>
<th></th>
<th>Lode</th>
<th></th>
<th>Power Tap</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Slope</strong></td>
<td><strong>Intercept</strong></td>
<td><strong>Slope</strong></td>
<td><strong>Intercept</strong></td>
</tr>
<tr>
<td></td>
<td><strong>Trial 1</strong></td>
<td><strong>Trial 2</strong></td>
<td><strong>Combined</strong></td>
<td><strong>Trial 1</strong></td>
</tr>
<tr>
<td></td>
<td>0.012 ± 0.001</td>
<td>0.012 ± 0.001</td>
<td>0.012 ± 0.001</td>
<td>0.012 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.423 ± 0.103</td>
<td>0.398 ± 0.094</td>
<td>0.410 ± 0.098*</td>
<td>0.526 ± 0.106</td>
</tr>
<tr>
<td></td>
<td>0.998 ± 0.002</td>
<td>0.998 ± 0.001</td>
<td>0.998 ± 0.001</td>
<td>0.997 ± 0.002</td>
</tr>
<tr>
<td></td>
<td><strong>Trial 2</strong></td>
<td></td>
<td><strong>Combined</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.012 ± 0.001</td>
<td></td>
<td>0.012 ± 0.001</td>
<td>0.012 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.518 ± 0.142</td>
<td></td>
<td>0.522 ± 0.123*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.996 ± 0.006</td>
<td></td>
<td>0.996 ± 0.004</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Combined</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.012 ± 0.001</td>
<td></td>
<td>0.012 ± 0.001</td>
<td>0.012 ± 0.001</td>
</tr>
<tr>
<td></td>
<td>0.522 ± 0.123*</td>
<td></td>
<td>0.522 ± 0.123*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.996 ± 0.004</td>
<td></td>
<td>0.996 ± 0.004</td>
<td></td>
</tr>
</tbody>
</table>
Figure 1-3. Graphical representation of the mean regression results for the submaximal oxygen consumption (L.min⁻¹) to power (Watts) relationships found while subjects were tested with the Power Tap (O) or Lode (♦).
Oxygen Consumption (L.min⁻¹)

Power Output (Watts)

- Power Tap: \( \dot{V}O_2 = 0.012 \times \text{Watts} + 0.522 \)
- Lode: \( \dot{V}O_2 = 0.012 \times \text{Watts} + 0.41 \)
Table 1-4. Measures of peak oxygen consumption (\(\dot{V}O_{2\text{peak}}\), L.min\(^{-1}\)), the power output corresponding to the time at which peak oxygen consumption was achieved (Power at \(\dot{V}O_{2\text{peak}}\), W), and the peak power output achieved during the test (Peak Power Output, W). Values are presented as means ± standard deviation. * Trial 2 significantly different to Trial 1, P < 0.05.
<table>
<thead>
<tr>
<th></th>
<th>Lode</th>
<th>Power Tap</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trial 1</td>
<td>Trial 2</td>
</tr>
<tr>
<td>$VO_{\text{2}}$ (L.min$^{-2}$)</td>
<td>4.63 ± 0.509</td>
<td>4.69 ± 0.469 *</td>
</tr>
<tr>
<td>Power at $VO_{\text{2}}$ (W)</td>
<td>394 ± 44</td>
<td>400 ± 41</td>
</tr>
<tr>
<td>Peak Power Output (W)</td>
<td>398 ± 45</td>
<td>400 ± 41</td>
</tr>
</tbody>
</table>
Discussion

Three questions were of primary importance to this investigation: 1) Does the Power Tap provide a valid measure of cycling power output? 2) Does the Power Tap provide a measure of power that is reliable both within and between units? and 3) Is the Power Tap a suitable means of measuring exercise stress during a laboratory-based graded exercise protocol?

On average, the Power Tap provides a measure of power output, which in absolute terms is very similar to that of a first principles dynamometer, but that small systematic differences are apparent between the two measures across workloads ranging from 100 W – 500 W. Further, the metabolic responses to a workload measured via the Power Tap are very similar to the responses observed when that workload is provided by a popular electromagnetically braked ergometer (Lode), although once again, a small but systematic difference likely exists between the intercept power of the Lode and that of the Power Tap.

Power Tap Validity:

The degree to which the Power Tap is providing a true measure of the power output applied to the bicycle is referenced here by a first principles external dynamometer and a popular laboratory-grade ergometer. Both dynamometer and Lode indicate that there is a slight systematic difference associated with the zero load (intercept) power output measured by the Power Tap. If one simply divides the mean difference in zero-load oxygen cost between the Lode trials and Power Tap trials from the metabolic validation (0.122 L.min⁻¹), by the mean slope of the \( \dot{V}O_2 \)-power
relationships (0.012 L.min⁻¹.Watt⁻¹), the estimated mechanical equivalent of the increased oxygen cost is some 9.3 Watts. While not identical, this value is relatively close to the intercept difference observed in the mechanical validation, and suggests a characteristic offset of zero-load power within and between Power Tap units. The difference in mean intercept values between the intra-unit and inter-unit trials also indicates a probable systematic difference between the intercepts of individual Power Tap units. However, the mean intra-unit to inter-unit difference observed here was very slight (2.65 W), and therefore not reflected in a variance difference between the two sets of trials.

The most likely cause of the intercept differences between the Power Tap and dynamometer is dissipation of power between the crank and the rear-hub, largely due to friction within the drive train (Martin et al. 1998). Indeed the findings of Martin suggest that this power loss is in the order of 1.9 – 6.7 watts across the range of power outputs studied here. The degree to which this difference indicates a measurement error is debatable, as for some purposes it is advantageous to eliminate drive-train friction from the measured power output (Grappe et al. 1997, Lim et al. Unpublished results), although most applications are targeted at assessing the exercise load, which is that power applied at the crank.

A second systematic difference observed when comparing the Power Tap and external dynamometer, was related to the slope or gain of the relationship. It appears when the Power Tap to Dynamometer relationship is viewed in isolation, that the Power Tap measures only 97% of the true increase in power for any given increment. While this seems a relatively small error at 3%, one must consider that at a power
output of 500 Watts this difference would amount to an underestimation of true power by some 21 Watts (including intercept error). Such an underestimation would have significant repercussions for estimations of physiological strain (Jeukendrup et al. 2000) and prediction of performance (Jeukendrup et al. 2001). To assess whether this slope error was a characteristic inherent to the Power Tap, we compared the Power Tap regressions depicted in figure 2 to those obtained from the scientific SRM during the same trials, for which results have not yet been described – figure 1-4.

Because both the SRM and Power Tap have similar slopes with respect to the dynamometer it appears likely that the source of error resulting in the apparent power loss is not inherent to the Power Tap, but is probably due to another element in the arrangement. This argument is further supported by the fact that the intercept difference one might expect between the crank-mounted SRM and hub-mounted Power Tap, is still apparent. Indeed, the identical slope values for the Power Tap and Lode obtained during the metabolic validation also suggest that a component of the mechanical arrangement other than the Power Tap is causing the slope discrepancies observed in the mechanical validation.

The potential sources of this error within the dynamometer arrangement are several. Initially it was thought that the use of a small rubber coupling device between the torque motor and bottom bracket may have resulted in some energy deficit, but Woods et al. 1994 note that their use of such a coupling device did not produce a measurable loss of power. Possible effects of temperature at the level of the commercial power meters are unlikely, as a progressively increasing temperature would cause a parallel overestimation of true power, due to strain gauge drift. With
Figure 1-4. Regression lines for all three mechanical sources (Dynamometer, SRM, and Intra-unit Power Tap) of power measurement.
Power meter power (W)

Dynamometer measured power (W)

- Line of Identity
  - Scientific SRM: $y = 0.968x + 2.20$
  - Power Tap: $y = 0.969x - 3.86$
increasing angular displacement of the lever arm acting to transfer the motor torque to
the scale it is possible that the moment arm acting on the scale was slightly altered, as
others (Eissing. 1982) have suggested for similar arrangements. Finally, it has been
noted that this external dynamometer does exhibit some degree of hysteresis in its
measurement of power but that this can be avoided by manually manipulating the
device at each workload increment (R. Wilber, personal communication). While this
manual manipulation was performed at each increment it remains possible that a
degree of hysteresis may have contributed to the observed slope errors. At this point
the source of the observed slope error is unclear but we believe that the parallel
evidence from the SRM and metabolic validation suggest that it is not an intrinsic
characteristic of the Power Tap device.

Power Tap Reliability:

While the variability of the $\dot{V}O_2$–power relationships were similar for the
Lode and Power Tap, both in terms of intercept (Lode SD = 0.098, Power Tap SD =
0.123) and slope (Lode SD = 0.001, Power Tap SD = 0.001), it is difficult to describe
this variability in absolute terms, as it is a function of both the variability inherent to
the two devices, and the variability inherent to the indirect calorimetry system. For
this reason the variability apparent in the metabolic validation will not be referred to
further.

The measures of random error obtained during the mechanical validation and
presented here, are three:
1. The degree to which the variation in Dynamometer measured power accounts for variation in Power Tap measured power, as indicated by the coefficient of determination ($r^2$).

2. The observed variability of the intercept measure.

3. The observed variability of the slope measure.

The mean coefficient of determination obtained across all Power Tap trials ($r^2 = 0.9998$) indicates that within any one trial, the Power Tap measure of power parallels that of the Dynamometer remarkably well. Indeed, the minimum $r^2$ value for any one trial at 0.9967, suggests that in the worst of 40 trials only 0.3% of the variability in the Power Tap measured power was not explained by the variability of the Dynamometer measure.

Also sturdy was the intercept measure of the Power Tap. The variability was consistent between the intra-unit (SD = 2.00 W) and inter-unit (SD = 2.36 W) trials, which suggests that parallel measures can be made with two separate units (as would be the case for racing observations) without increasing the likelihood of error. The range of intercept values for the twenty intra-unit trials was 7.28 W (-7.68 W to -0.399 W), and for the twenty units from the inter-unit trials the range was 9.53W (-11.34 W to -1.81W). While these differences in variability are worst case, and do not represent a large percentage of the average power output maintained by elite cyclist’s while racing (Martin et al. 2001, Jeukendrup et al. 2001) they may contribute to the elevated variability observed when these devices are employed for more subtle purposes, such as the measurement of rolling resistance. The reasons for this
variability in the Power Tap intercept are unclear, but may be inherent to the device, or due to some other element of the arrangement. Information gleaned from the SRM suggests that this variability is not isolated to the Power Tap as the standard deviation values were similar (SRM SD = 1.69 W, range = 6.26 W), and the variance of the Power Tap intercept was not different to that of the SRM ($P = 0.47$). These two intercepts were also moderately correlated ($r = 0.66$), indicating that approximately 44% of the observed variance was common to both commercial power meters. These observations suggest that the variability of the Power Tap intercept is not likely to be solely intrinsic, and is similar in magnitude to that of the SRM.

The final aspect of interest is the variability surrounding the mean slope value of the Power Tap – Dynamometer regressions. Similar to the intercept variability, it appears that the inter-unit variability of the Power Tap is largely determined by the trial-to-trial variation inherent to the mechanism rather than differences between units – the intra-unit variability (SD = 0.0086 W) was not different to the inter-unit variability (0.0112 W). The range of slopes observed for the Power Tap were 0.0344 and 0.0414 W.W$^{-1}$ during the intra-unit and inter-unit comparisons, respectively. Again these values were similar to those of the SRM (SD = 0.0083 W, range = 0.0309 W.W$^{-1}$), and again, it was not possible to determine whether the observed variability in the two devices is inherent to each, or due to some combination of elements external to the devices but included within the experimental arrangement.

We believe these findings indicate that the Power Tap cycle-mounted power meter provides both a valid and reliable measure of power output while cycling. The systematic differences observed in terms of the intercept, both mechanical and
metabolic, can be explained by drive-train friction, and accounted for when crank power is the desired measure. The systematic underestimation of dynamometer power by both the Power Tap and scientific SRM, in combination with the lack of a slope difference when comparing the Power Tap and Lode ergometers metabolically, likely indicates a slight error intrinsic to the dynamometer rather than the portable power meters. With reference to reliability, the variation both within and between Power Tap units was similar in terms of both the slope and intercept measures. Furthermore, all measures of Power Tap variability were comparable to those of the scientific grade SRM and may therefore be caused by factors external to both devices.

It appears that the Power Tap is a suitable tool for scientific-standard measurement of cycling power output. It has been shown here to be a valid and reliable tool for cycle-based graded exercise stress testing, and for that reason it is likely to be equally valid and reliable in field-based contexts where power output remains fairly constant, such as the time-trial. The greatest limitation of the current investigation is that no assessment was made of validity and reliability when power is rapidly altered, as is a characteristic of many cycling events (Martin et al. 2001, Lim et al. Unpublished results). While there is no evidence from this investigation to suggest the Power Tap is a less valid or reliable measure of power under a variable load, for one to be certain that it accurately and precisely tracks rapid oscillations in power output, further data should be collected with a dynamometer arrangement capable of creating such rapid oscillations.
Acknowledgements

This work was partially funded by Graber Products Inc. (Madison, WI). The results of this investigation do not constitute endorsement of the Power Tap power meter either by the authors or by the American College of Sports Medicine.

Many thanks to Randy Wilbur and the United States Olympic Committee for use of the external dynamometer described here, and also to Rodger Kram Ph.D. for his invaluable advice and assistance throughout
References


CHAPTER III: A COMPARISON OF HEART RATE AND POWER OUTPUT IN DESCRIBING THE DEMANDS OF A SIX-DAY CYCLING STAGE RACE

Abstract

Purpose: To compare the demands of a six-day stage race using field measures of power and heart rate (HR) in men (n=8) and women (n=10) from North American based professional cycling teams. Methods: Power output was measured using rear hub (Power Tap®, Madison WI) and crank (SRM®, Julich Germany) mounted power meters, while HR was monitored via radio telemetry. Men and women competed over the same distances and courses during a prologue (4 km), 4 circuit/road races (mean ± SD: 118 ± 23 km), and a criterium (47 km). Performance measures, including HR versus power output regressions, were assessed during a graded exercise stress test in the laboratory within two weeks of the race. Results (mean ± SD): \( V_\text{O}_2 \text{peak} \), power at \( V_\text{O}_2 \text{peak} \), and power at lactate threshold (LT) for men vs. women were 68 ± 3 vs. 54 ± 4 ml·kg\(^{-1}\)·min\(^{-1}\), 416 ± 23 vs. 313 ± 27 watts, and 288 ± 11 vs. 203 ± 22 watts, respectively. In men, the actual power vs. HR estimate of power in the prologue, circuit/road races, and criterium was 405 vs. 353, 247 vs. 289, and 278 vs. 317 watts, respectively, resulting in an estimated energy expenditure of 143 vs. 124, 2500 vs. 2960, and 1109 vs. 1259 kcals, respectively. In women, the actual power vs. HR estimate of power in the prologue, circuit/road races, and criterium was 295 vs. 254, 160 vs. 192, and 205 vs. 237 watts, respectively, resulting in an estimated energy expenditure of 117 vs. 99, 2059 vs. 2441, and 910 vs. 1050 kcals, respectively. Compared to the actual power output, HR significantly underestimated energy expenditure and power during the prologue and overestimated during the circuit/road
races and criterium, with no difference between genders. In men, using power vs. HR the percent time spent below, at, and above LT was 29 vs. 4%, 9 vs. 11%, and 62 vs. 85%, respectively in the prologue, 57 vs. 33%, 10 vs. 28%, and 33 vs. 39%, respectively in the circuit/road races, and 51 vs. 10%, 6 vs. 27%, and 43 vs. 63%, respectively in the criterium. In women, using power vs. HR the percent time spent below, at, and above LT was 24 vs. 3%, 7 vs. 3%, and 69 vs. 94%, respectively in the prologue, 62 vs. 42%, 10 vs. 28%, and 28 vs. 30%, respectively in the circuit/road races, and 50 vs. 8%, 8 vs. 21%, and 42 vs. 71%, respectively in the criterium.

Relative to power output, HR significantly underestimated the percent time spent below LT in the prologue, circuit/road races, and criterium, overestimated time spent at LT in the circuit/road races and criterium, and overestimated time spent above LT in the prologue and criterium, with no difference between genders. Conclusions: Heart rate and power provide different descriptions of competitive cycling demands with respect to power output, energy expenditure, and distribution of power output.

**Introduction**

In the laboratory, there is a significant and reproducible relationship between power output and an individual’s heart rate, perceived exertion, and metabolic response during graded or steady state exercise (8, 17, 22, 26, 32, 33, 38, 40). As a result, outside of the laboratory, simple measures like heart rate and perceived exertion are commonly used to quantify the demands of training and competition in a number of sports and physical activities (16, 19, 31, 34, 45, 52, 55). Notably, heart rate is often used to estimate energy expenditure or work as well as the distribution of
exercise intensity or power output in activities where speed is not an accurate measure of these demands because of variations in wind, terrain, aerodynamics, and pace. Accordingly, a significant number of studies have used heart rate to estimate the intensity and energy requirements of training and/or competition in road cycling events (19, 32, 38, 41, 49, 50, 52). In this particular setting, however, the accuracy of heart rate relative to actual measures of power output remains controversial (1, 9, 30, 43, 53).

Although heart rate can be an excellent estimate of power and work in controlled settings, there are a number of environmental, psychological, and physiological factors that can dissociate the relationship between heart rate and power during steady state exercise (1). These factors include, cardiovascular drift associated with changes in peripheral blood flow and dehydration during prolonged exercise in the heat (13, 58, 60), acute changes in altitude (44, 65), changes in circulating catecholamines (69), the psychological state of the individual (10, 57), variations in fitness (29), and intensified training and/or overreaching (6, 62). During non-steady state exercise conditions, changes in the pattern of power output, especially during high intensity intermittent exercise, can drastically affect the heart rate response at the same average power output (3, 9, 36, 51). In addition, the range of heart rate as an intensity measure is fixed to a physiological minimum and maximum. The rate at which heart rate can respond to changes in power output is also limited (43, 53). As a result, heart rate response does not reflect the anaerobic energy contribution during supra-maximal efforts or sudden changes in energy demand during brief pauses or drops in power output (4). In addition, because of this delay, heart rate may not
adequately reflect oxygen consumption or the anaerobic energy contribution during non-steady exercise (9).

With the advent of cycle mounted power meters embedded in the crank or rear hub of racing bicycles, it is now possible to directly monitor the demands of road cycling in field settings. Accordingly, the purpose of this study was to directly compare how measures of heart rate and power output describe the distribution of exercise intensity and energy expenditure during a six-day professional stage race. Because of the many factors that can affect the relationship between power and heart rate, we hypothesize that compared to power output, heart rate will not accurately predict the average power output, distribution of power output, or give the same estimate of energy expenditure. Specifically, we believe that in short events with a significant anaerobic energy contribution, heart rate will underestimate the average power output and energy expenditure and not adequately reflect time spent below the lactate threshold. In long events with a significant aerobic energy contribution, we believe that heart rate will overestimate the average power output and energy expenditure, underestimating time spent below lactate threshold and overestimating time spent above lactate threshold.

**Methods**

*Subjects:*

Subjects included eight men and ten women from UCI division III and II North American based professional cycling teams. All subjects volunteered and gave
their informed consent to participate under the guidelines and approval of the University of Colorado at Boulder Human Research Committee.

Field Monitoring:

Athletes were monitored during competition at the Tour De Toona stage race in Altoona, Pennsylvania during the peak of the North American racing season. The stage race selected was unique in that all men and women competed over the same courses, distances, and for the same prize money throughout the six days of competition. Competition began with a prologue (4 km) followed by 4 circuit/road races (mean ± SD: 118 ± 23 km), and ended with a criterium (47 km) on the final day.

During competition in the field, power was monitored for each subject with crank (SRM, Julich, Germany) or hub (Power Tap, Madison, Wisconsin) based power meters while heart rate was monitored via radio telemetry (SRM or Power Tap). Both types of power meters have been shown to be both reliable and valid measures of power (20). All power meters measured external power output (watts), ground velocity (km·hr⁻¹), cadence (revolutions·min⁻¹, rpm), heart rate (beats·min⁻¹, bpm), and time with power measured at a frequency of 61 Hz (Power Tap) or 200 Hz (SRM) and data recorded in pre-determined increments of 1.26 to 3 seconds (Power Tap) or 1 to 2 seconds (SRM). As instructed by the manufacturers, each power meter was calibrated against a zero watt reference before each event. After each race, data was immediately downloaded to a laptop computer.

Although all subjects were encouraged to utilize a power meter for each event of the stage race, their choice of equipment was ultimately left to their discretion. At the same time, two of the men and two of the women crashed or dropped out of the
stage race before the final criterium. In addition, on a number of occasions, subjects were not monitored due to complete failure of the power meter, missing data within the downloaded file, a broken rear wheel, or a rear flat tire. Thus, we were unable to monitor every subject during each event. In the prologue, 6 of the men and all 10 of the women were monitored. During the circuit/road races, 17 of 32 possible race recordings were made in the men while 36 of 40 possible race recordings were made in the women. Finally, in the criterium, 4 of 6 possible race recordings were made in the men while 5 of 8 possible race recordings were made in the women.

_Laboratory Monitoring:_

Within two weeks prior to or after the race, subjects were flown to the Applied Exercise Science Laboratory in Boulder, CO to have their performance assessed during a submaximal and maximal graded exercise stress test (GXT). The GXT was conducted on an electronically braked ergometer (Lode Excalibur, Groningen, Netherlands) that was adjusted to match each subject’s bicycle and fitted with each subject’s pedal system. The submaximal portion of the GXT began at 100 W for women and 150 W for men and was incremented by 25 W every 4 minutes until a rating of perceived exertion of 16 to 17 (Borg 6-20 scale). Subjects were then allowed 10 minutes of active (50-100 W) or passive recovery. Immediately thereafter, the maximal portion of the GXT began at the penultimate stage of the submaximal GXT with power incremented by 25 W per minute until volitional fatigue. All tests were conducted at an altitude of 1,625 meters (5,330 feet) with an average barometric pressure, temperature, and humidity of 629.4 ± 4.2 mmHg, 22.5 ± 1.2 °C, and 36.3 ±
7.2%, respectively. In addition, a standard fan set at high was used to cool subjects throughout each test.

Metabolic variables (VO$_2$, VCO$_2$, and VE) were measured every 15 seconds through computer assisted indirect calorimetry using Parvomedics software and hardware to integrate input from a Validyne pressure transducer linked to a Hans Rudolph pneumotach measuring inspired ventilation and a Perkin Elmer mass spectrometer sampling from a 4-liter mixing chamber. Before each test, gas fractions were calibrated against a primary standard within the physiologic range (≈ 15% O$_2$ & 5% CO$_2$), while the pneumotach was calibrated using a 3-liter syringe at 5 distinct flow rates (≈ 50 l·min$^{-1}$ to 300 l·min$^{-1}$ ATPS). In addition, a 3-minute mechanical check was performed before and after each test using the primary standard and a flow rate of 60 l·min$^{-1}$ ATPS. From pre to post mechanical checks ventilation remained within 1% and gas fractions within 0.3% of original calibration values. Peak oxygen consumption (VO$_2$ peak) was assessed as the highest VO$_2$ for a 30-second period, while peak power was assessed as the power output associated with VO$_2$ peak. Using a linear regression between power output and oxygen consumption from the submaximal data, economy was calculated as the ratio between power output and oxygen cost at each individual’s lactate threshold (Watts·l O$_2$ at LT). In addition, the ratio between mechanical energy production (kcals) and the metabolic energy expenditure (kcals) during each submaximal stage was calculated and the mean from all stages was used as a measure of gross mechanical efficiency.

Heart rate was measured at the end of each minute via radio telemetry (Polar Vantage, Polar Electro, Finland). From the submaximal measures of heart rate and
power output, linear regression equations describing the power versus heart rate relationship were calculated for each subject. In all subjects, heart rate was significantly correlated to power ($r > 0.99, p < 0.001$).

Blood lactate was measured at rest and over the last minute of each submaximal stage, and 2-minutes post volitional fatigue. For each sample, approximately 50 $\mu l$ of blood was drawn via finger pricks into a 75 $\mu l$ capillary syringe. Twenty-five $\mu l$ was then mixed with a “cocktail” containing 50 $\mu l$ of a buffer, lysing (Triton XL-100), and anti-glycolytic (sodium fluoride) solution. Lactate was sampled using a YSI 2300 lactate analyzer. Before each test, the lactate analyzer was calibrated against a known standard, and re-calibrated every 15 minutes. The lactate threshold was defined as a point 1 mM above a baseline that included resting lactate (Coyle REF). The average value for these points determined from 3 independent observers was used in data analysis. No significant difference was found between observers.

Within two days of the laboratory test, body composition was assessed using dual energy x-ray absorptiometry. Extended analysis was performed on each scan by three independent observers. No significant difference was found between observers. For each subject, the mean between observers was used in data analysis.

Data Analysis:

Raw data (time, power, speed, cadence, and heart rate) from downloads was first analyzed using Power Coach™ software (Kochli Sport, Sonvilier, Switzerland) to match the time in the data file with the actual time recorded for each individual
subject by race officials. The distance from this isolated data was then checked to ensure that it matched the actual distance of the course. If the time and distance did not match, the data was not used in analysis.

In some cases, radio interference would break the heart rate signal from the subject. If this break was less than 30 seconds, any zero heart rate value was interpolated using code written in Matlab® (The Mathworks Inc, Berkeley, CA). At the same time, if a new HR max was identified by Matlab the user was prompted to either accept or exclude the value. In many cases, the value was non-physiologic (> 15 beats of any previously recorded HR value). In addition, single heart rate outliers (Δ > 10 beats/sec) were visually identified and interpolated.

After the heart rate data was assessed all additional analyses was completed using Matlab. Specifically, linear regression equations from the submaximal laboratory data relating power, heart rate, and energy expenditure were used to estimate kcals during racing from power and heart rate. The laboratory power-heart rate relationship was also used to estimate power during racing from heart rate.

Lactate threshold was used as a reference point for three intensity zones – below lactate threshold (< 90% of LT), at lactate threshold (90 to 110% of LT), and above lactate threshold (> 110% of LT). Using the lactate threshold power as a reference point, the appropriate intensity ranges for power were set. Using the laboratory power to heart rate relationship, heart rates corresponding to these power zones were also established. In addition, VO₂ peak was used as a reference point for four intensity zones – low (< 50% of VO₂ peak, moderate (50 to 70%), high (70 to 90%), and maximal (> 90%).
A 2x2x3 factorial ANOVA design was used to compare differences between gender (men vs. women), intensity measure (HR vs. PW), and event type (prologue vs. circuit/rad race, vs. criterium). Statistical significance was set at a p-value < 0.065. All statistics were calculated using Stat View (SAS Institute Inc., Cary, NC).

**Results**

*Subject Characteristics:*

Descriptive data for our subjects from the laboratory testing is listed in Table 2-1. The mean (± SD) age of our male and female subjects was not significantly different at 28.3 ± 3.6 and 28.8 ± 5.9 years, respectively. The men had been racing on average for 10.5 ± 4.8 years, while the women had raced significantly less time at 7.0 ± 3.7 years. Men were also significantly heavier and taller than women at 70.5 ± 3.5 kg and 178.3 ± 6.2 cm versus 60.5 ± 4.9 kg and 167.7 ± 4.8 cm.

From the submaximal and maximal testing the men had a mean VO₂ peak, power at VO₂ peak, and power at LT of 67.57 ± 2.48 ml·kg⁻¹·min⁻¹, 415.6 ± 22.9 watts, and 288.6 ± 11.3 watts, respectively. Compared to the men, women had significantly lower values for VO₂ peak, power at VO₂ peak, and power at LT of 53.91 ± 3.81 ml·kg⁻¹·min⁻¹, 312.5 ± 27.0 watts, and 202.7 ± 22.5 watts, respectively. No difference, however, was found in LT between men and women if expressed as a % of VO₂ peak (l·min⁻¹), with both men and women having a VO₂ at LT of 77 ± 4% of VO₂ peak. Finally, no difference was found between men and women in gross mechanical efficiency or economy, which was 22.4 ± 0.7% or 76.2 ± 2.9 watts·l O₂⁻¹ for the men and 22.2 ± 1.2% or 80.9 ± 5.5 watts·l O₂⁻¹ for the women.
Table 2-1. Descriptive data for men and women from laboratory testing. Results include age, height, weight, years racing, and physiological parameters important to endurance performance such as $\text{VO}_2$ max, the lactate threshold and economy.
<table>
<thead>
<tr>
<th></th>
<th>Men</th>
<th>Women</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>28.3 ± 3.6</td>
<td>28.8 ± 5.9</td>
</tr>
<tr>
<td>Years Racing</td>
<td>10.5 ± 4.8 *</td>
<td>7.0 ± 3.7</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.3 ± 6.2 *</td>
<td>167.7 ± 4.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>70.5 ± 3.5 *</td>
<td>60.5 ± 4.9</td>
</tr>
<tr>
<td>% Body Fat</td>
<td>8.9 ± 1.5 *</td>
<td>17.9 ± 3.8</td>
</tr>
<tr>
<td>Bone Density (g·cm⁻³)</td>
<td>1.19 ± 0.09</td>
<td>1.18 ± 0.08</td>
</tr>
<tr>
<td>VO₂ peak (l·min⁻¹)</td>
<td>4.75 ± 0.23 *</td>
<td>3.24 ± 0.20</td>
</tr>
<tr>
<td>VO₂ peak (ml·kg⁻¹·min⁻¹)</td>
<td>67.6 ± 2.5 *</td>
<td>53.9 ± 3.8</td>
</tr>
<tr>
<td>VO₂ peak power (watts)</td>
<td>415.6 ± 22.9 *</td>
<td>312.5 ± 27.0</td>
</tr>
<tr>
<td>VO₂ peak power (watts·kg⁻¹)</td>
<td>5.91 ± 0.41 *</td>
<td>5.19 ± 0.58</td>
</tr>
<tr>
<td>LT power (watts)</td>
<td>288.6 ± 11.3 *</td>
<td>202.7 ± 22.5</td>
</tr>
<tr>
<td>LT power (watts·kg⁻¹)</td>
<td>4.11 ± 0.29 *</td>
<td>3.36 ± 0.34</td>
</tr>
<tr>
<td>LT power as % of VO₂ peak power</td>
<td>69.4 ± 4.2</td>
<td>64.9 ± 4.8</td>
</tr>
<tr>
<td>LT as % of VO₂ peak (l·min⁻¹)</td>
<td>77 ± 4</td>
<td>77 ± 4</td>
</tr>
<tr>
<td>Gross mechanical efficiency (%)</td>
<td>22.4 ± 0.7</td>
<td>22.2 ± 1.2</td>
</tr>
<tr>
<td>Economy</td>
<td>76.2 ± 2.9</td>
<td>80.9 ± 5.5</td>
</tr>
<tr>
<td>Peak Laboratory HR (bpm)</td>
<td>187 ± 9 * †</td>
<td>180 ± 12 †</td>
</tr>
<tr>
<td>Peak Field HR (bpm)</td>
<td>195 ± 8 *</td>
<td>186 ± 10</td>
</tr>
</tbody>
</table>

* Significantly different from women.  
† Significantly different from field measure.
Of note, the peak HR during laboratory testing was $187 \pm 9$ bpm in men and $180 \pm 12$ bpm in women. These values were significantly lower than the peak HR found during the field testing, which was $195 \pm 8$ bpm in men and $186 \pm 10$ bpm in women. These differences, however, may have been due to the different sampling rate used during laboratory testing (15 seconds) and in the field (1 to 3 seconds).

**Average Power Output:**

The mean ± SD power output and the heart rate estimate of power output in absolute values and as a % of LT power and VO$_2$ peak power are listed in Table 2-2, for women and men in the prologue, circuit/road races, and criterium. For each event, the heart rate estimate of power output was different from the actual measured power output. Likewise, in all events, women produced less power than men whether that power was actually measured or estimated by heart rate. As a percent of lactate threshold or VO$_2$ peak power, however, no difference was found between men and women.

In the prologue, the average power output was significantly underestimated by heart rate. The actual mean ± SD power output was $295 \pm 26$ watts or $108 \pm 12\%$ of VO$_2$ peak power for women ($n = 6$) and $405 \pm 33$ watts or $105 \pm 4\%$ of VO$_2$ peak power for men ($n = 5$). At an average heart rate of $173 \pm 11$ bpm for women and $176 \pm 7$ bpm for men, the heart rate estimate of power was $254 \pm 21$ watts or $93 \pm 7\%$ of VO$_2$ peak power for women and $353 \pm 30$ watts or $92 \pm 8\%$ of VO$_2$ peak power for men. The mean ± SD time for the prologue was $00:06:05 \pm 00:00:10$ for the women and $00:05:29 \pm 00:00:17$ for the men. No significant correlation was found between
Table 2-2. The actual mean ± SD power output (Power) versus an estimate of power output calculated from the average heart rate for each subject and their individual linear regression relating power output to heart rate in the laboratory (HR est). Values are given as the absolute wattage and as a % of LT power and VO₂ peak power for women (W) and men (M) in the prologue, circuit/road races, and criterium.
<table>
<thead>
<tr>
<th></th>
<th>Power Output (Watts)</th>
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<tbody>
<tr>
<td></td>
<td>Prologue</td>
<td>Circuit/Road Races</td>
<td>Criterium</td>
<td></td>
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<tr>
<td></td>
<td>Power *</td>
<td>HR est</td>
<td>Power *</td>
<td>HR est</td>
</tr>
<tr>
<td>W</td>
<td>Absolute †</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>295 ± 26</td>
<td>254 ± 21</td>
<td>160 ± 16</td>
<td>192 ± 27</td>
</tr>
<tr>
<td></td>
<td>% LT</td>
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<tr>
<td></td>
<td>147 ± 19</td>
<td>126 ± 8</td>
<td>79 ± 10</td>
<td>95 ± 12</td>
</tr>
<tr>
<td></td>
<td>% VO₂ peak</td>
<td></td>
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<tr>
<td></td>
<td>108 ± 12</td>
<td>93 ± 7</td>
<td>59 ± 7</td>
<td>70 ± 9</td>
</tr>
<tr>
<td>M</td>
<td>Absolute</td>
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<tr>
<td></td>
<td>405 ± 33</td>
<td>353 ± 30</td>
<td>247 ± 25</td>
<td>289 ± 30</td>
</tr>
<tr>
<td></td>
<td>% LT</td>
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<tr>
<td></td>
<td>139 ± 9</td>
<td>121 ± 14</td>
<td>86 ± 9</td>
<td>101 ± 12</td>
</tr>
<tr>
<td></td>
<td>% VO₂ peak</td>
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</tr>
<tr>
<td></td>
<td>105 ± 4</td>
<td>92 ± 8</td>
<td>64 ± 6</td>
<td>75 ± 8</td>
</tr>
</tbody>
</table>

* Significantly different from HR estimate of power (p < 0.05).
† Significantly different from men (p < 0.05).
power output and finishing time in the prologue for women \((r = -0.27, p > 0.05)\) or men \((r = 0.12, p > 0.05)\).

In the circuit/road races, the average power output was significantly overestimated by heart rate. The actual mean ± SD power output was 160 ± 16 watts or 59 ± 7% of \(VO_2\) peak power for women \((n = 36)\) and 247 ± 25 watts or 64 ± 6% of \(VO_2\) peak power for men \((n = 17)\). At an average heart rate of 148 ± 8 bpm for the women and 156 ± 9 for the men, the heart rate estimate of power was 192 ± 27 watts or 70 ± 9% of \(VO_2\) peak power for women and 289 ± 30 watts or 75 ± 8% of \(VO_2\) peak power for men. The mean ± SD time for the circuit/road races was 03:24:41 ± 00:50:04 for the women and 02:39:59 ± 00:46:02 for the men. No significant correlation was found between power output and finishing time in any of the circuit/road races for women \((r = 0.10, p > 0.05)\) or men \((r = -0.20, p > 0.05)\).

In the criterium, the average power output was significantly overestimated by heart rate. The actual mean ± SD power output was 295 ± 26 watts or 74 ± 4% of \(VO_2\) peak power for women \((n = 5)\) and 405 ± 33 watts or 75 ± 4% of \(VO_2\) peak power for men \((n = 4)\). At an average heart rate of 165 ± 9 bpm for the women and 164 ± 4 for the men, the heart rate estimate of power was 254 ± 21 watts or 86 ± 4% of \(VO_2\) peak power for women and 353 ± 30 watts or 85 ± 2% of \(VO_2\) peak power for men. All of the women finished the criterium in a time of 01:09:34, while all of the men finished in 01:02:20 seconds. Because all men and women finished in the same time, no correlation was found between power output and finishing time. Average power and heart rate estimates of power for each of the three types of events for men and women are graphically displayed in Figure 2-1.
Figure 2-1. The mean (± SD) power output and heart rate estimate of power output in men and women during the prologue, circuit/road races, and criterium in relationship to the mean lactate threshold for each gender. The mean time (hr:min:sec) for each event and gender is also given.
Power (watts)

LT Power

Women Men Women Men


Circuit / Road Races Criterium

* Significantly different from HR estimate of power (p < 0.05).
† Significantly different from men (p < 0.05).
Energy Expenditure:

The mean ± SD energy expenditure (Kcals) estimated from power output and heart rate are listed in Table 2-3 for women and men in the prologue, circuit/road races, and criterium. For each event, the heart rate estimate of energy expenditure was significantly different from the power output estimate of energy expenditure. Likewise, in all events, women consumed significantly less energy than men whether energy expenditure was actually measured or estimated by heart rate.

In the prologue, the energy expenditure was significantly underestimated by heart rate. The mean ± SD energy expenditure estimated from power was 117 ± 13 Kcals for women (n = 6) and 143 ± 13 Kcals for men (n = 5), while the heart rate estimate of energy expenditure was 99 ± 1 Kcals for women and 124 ± 14 Kcals for men.

In the circuit/road races, the energy expenditure was significantly underestimated by heart rate. The mean ± SD energy expenditure estimated from power was 2059 ± 613 Kcals for women (n = 6) and 2500 ± 459 Kcals for men (n = 5), while the heart rate estimate of energy expenditure was 2441 ± 620 Kcals for women and 2960 ± 799 Kcals for men.

In the criterium, the energy expenditure was significantly underestimated by heart rate. The mean ± SD energy expenditure estimated from power was 910 ± 45 Kcals for women (n = 6) and 1109 ± 110 Kcals for men (n = 5), while the heart rate estimate of energy expenditure was 1050 ± 58 Kcals for women and 1259 ± 121 Kcals for men. Energy expenditure results from power and heart rate estimates for
Table 2-3. The mean ± SD energy expenditure (Kcals) estimated from the average power output and the laboratory regression relating power to energy expenditure for each individual (Power est). Also given is the mean ± SD energy expenditure (Kcals) estimated from the average heart rate and laboratory regression relating heart rate to energy expenditure for each individual (HR est). Values are given for women (W) and men (M) in the prologue, circuit/road races, and criterium.
<table>
<thead>
<tr>
<th></th>
<th>Prologue</th>
<th>Circuit/Road Races</th>
<th>Criterium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Power *</td>
<td>HR est</td>
<td>Power *</td>
</tr>
<tr>
<td>W †</td>
<td>117 ± 13</td>
<td>99 ± 7</td>
<td>2059 ± 613</td>
</tr>
<tr>
<td>M</td>
<td>143 ± 13</td>
<td>124 ± 14</td>
<td>2500 ± 459</td>
</tr>
</tbody>
</table>

* Significantly different from HR estimate of energy expenditure (p < 0.05).
† Significantly different from men (p < 0.05).
each of the three types of events for men and women are graphically displayed in Figure 2-2.

*Time Relative to LT:*

The percent time spent below, at, and above lactate threshold calculated from power (PW) and heart rate (HR) for men and women in the prologue, circuit/road races, and criterium are presented in Table 2-4. No significant difference was found in the distribution of power output or heart rate in men and women.

In the prologue, heart rate underestimated the percent time spent below LT and overestimated the time spent above LT, with no difference found at LT. In women, the mean ± SD percent time spent below, at, and above LT from measures of power was 24 ± 7 %, 7 ± 3 %, and 69 ± 9 %, respectively, while the percentages from heart rate was 3 ± 1 %, 3 ± 3 %, and 94 ± 4 %, respectively. In the men, the mean ± SD percent time spent below, at, and above LT from measures of power was 29 ± 5 %, 9 ± 3 %, and 62 ± 6 %, respectively, while the percentages from heart rate was 4 ± 2 %, 11 ± 14 %, and 85 ± 16 %, respectively. Graphical results for the prologue are presented in Figure 2-3.

In the circuit/road races, heart rate underestimated the percent time spent below LT and overestimated the time spent at LT, with no difference found above LT. In women, the mean ± SD percent time spent below, at, and above LT from measures of power was 62 ± 8 %, 10 ± 3 %, and 28 ± 7 %, respectively, while the percentages from heart rate was 42 ± 21 %, 28 ± 7 %, and 30 ± 18 %, respectively. In
Figure 2-2. The mean (±SD) energy expenditure in Kcals estimated from measures of power output or heart rate response in women and men during the prologue, circuit/road races, and criterium.
* Significantly different from HR estimate of energy expenditure (p < 0.05).

† Significantly different from men (p < 0.05).
Table 2-4. The percent time spent below (BE), at (AT), and above (AB) lactate threshold calculated from power (PW) and heart rate (HR) for men (M) and women (W) in the prologue, circuit/road races, and criterium. No significant difference was found in the distribution of power output or heart rate in men and women, though significant difference was found between heart rate and power estimates where noted.
<table>
<thead>
<tr>
<th></th>
<th>% Time spent below (BE), at (AT), and above (AB) Lactate Threshold</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prologue</td>
<td>Circuit/Road Races</td>
<td>Criterium</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BE</td>
<td>AT</td>
<td>AB</td>
<td>BE</td>
</tr>
<tr>
<td>W PW</td>
<td>24 ± 7</td>
<td>7 ± 3</td>
<td>69 ± 9</td>
<td>62 ± 8</td>
</tr>
<tr>
<td></td>
<td>3 ± 1</td>
<td>3 ± 3</td>
<td>94 ± 4</td>
<td>42 ± 21</td>
</tr>
<tr>
<td>M PW</td>
<td>29 ± 5</td>
<td>9 ± 3</td>
<td>62 ± 6</td>
<td>57 ± 6</td>
</tr>
<tr>
<td></td>
<td>4 ± 2</td>
<td>11 ± 14</td>
<td>85 ± 16</td>
<td>33 ± 22</td>
</tr>
</tbody>
</table>

* Significantly different from heart rate (p < 0.05).
Figure 2-3. The mean (±SD) percent time spent below, at, and above LT during the prologue in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
the men, the mean ± SD percent time spent below, at, and above LT from measures of power was 57 ± 6 %, 10 ± 2 %, and 33 ± 5 %, respectively, while the percentages from heart rate was 33 ± 22 %, 28 ± 9 %, and 39 ± 22 %, respectively. Graphical results for the circuit/road races are presented in Figure 2-4.

In the criterium, heart rate underestimated the percent time spent below LT and overestimated the time spent at and above LT. In women, the mean ± SD percent time spent below, at, and above LT from measures of power was 50 ± 4 %, 8 ± 2 %, and 42 ± 2 %, respectively, while the percentages from heart rate was 8 ± 1 %, 21 ± 19 %, and 71 ± 33 %, respectively. In the men, the mean ± SD percent time spent below, at, and above LT from measures of power was 51 ± 4 %, 6 ± 2 %, and 43 ± 4 %, respectively, while the percentages from heart rate was 10 ± 13 %, 27 ± 16 %, and 63 ± 23 %, respectively. Graphical results for the criterium are presented in Figure 2-5.

*Time Relative to VO₂ peak:*

The percent time spent at low, moderate, high, and maximal intensities calculated from power (PW) and heart rate (HR) for men and women in the prologue, circuit/road races, and criterium are presented in Table 2-5. No significant difference was found in the distribution of power output or heart rate in men and women.

In the prologue, heart rate underestimated the percent time spent at low and moderate intensities, overestimated the time at high intensities, with no difference at maximal intensities. In women, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power was 16 ± 4%, 9 ± 3%, 12 ± 4% and 63 ± 5%, respectively, while the percentages from heart rate was 1 ± 1%, 2 ± 1%,
Figure 2-4. The mean (±SD) percent time spent below, at, and above LT during the circuit/road races in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
Figure 2-5. The mean (±SD) percent time spent below, at, and above LT during the criterium in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
Table 2-5. The percent time spent at low (L, < 50% of VO₂ peak), moderate (MO, 50-70%), high (H, 70-90%), and maximal (MA, > 90%) intensities calculated from power (PW) and heart rate (HR) for men (M) and women (W) in the prologue, circuit/road races, and criterium. No significant difference was found in the distribution of power output or heart rate in men and women, though significant difference was found between heart rate and power estimates where noted.
<table>
<thead>
<tr>
<th></th>
<th>Prologue</th>
<th>Circuit/Road Races</th>
<th>Criterium</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>L</td>
<td>MO</td>
<td>H</td>
</tr>
<tr>
<td>W PW</td>
<td>16</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>±4</td>
<td>±3</td>
<td>±4</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>HR</td>
<td>1</td>
<td>2</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>±1</td>
<td>±1</td>
<td>±22</td>
</tr>
<tr>
<td>M PW</td>
<td>17</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>±3</td>
<td>±2</td>
<td>±2</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
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<td>2</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>±1</td>
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<td>±16</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

* Significantly different from heart rate (p < 0.05).
39 ± 22%, and 58 ± 23%, respectively. In men, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power was 17 ± 3%, 11 ± 2%, 15 ± 2% and 57 ± 1%, respectively, while the percentages from heart rate was 2 ± 1%, 2 ± 1%, 38 ± 18%, and 58 ± 16%, respectively. Graphical results for the prologue are presented in Figure 2-6.

In the circuit/road races, heart rate underestimated the percent time spent at low intensities, overestimated time at moderate and high intensities, and underestimated the time at maximal intensities. In women, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power was 47 ± 7%, 17 ± 3%, 14 ± 3% and 22 ± 2%, respectively, while the percentages from heart rate was 13 ± 13%, 32 ± 9%, 42 ± 14%, and 12 ± 12%, respectively. In men, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power was 42 ± 6%, 17 ± 2%, 15 ± 2% and 27 ± 2%, respectively, while the percentages from heart rate was 7 ± 7%, 27 ± 14%, 49 ± 15%, and 17 ± 13%, respectively. Graphical results for the circuit/road races are presented in Figure 2-7.

In the criterium, heart rate underestimated the percent time spent at low and moderate intensities, overestimated the time at high intensities, and underestimated time at maximal intensities. In women, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power was 38 ± 2%, 12 ± 1%, 12 ± 1% and 38 ± 1%, respectively, while the percentages from heart rate was 0 ± 0%, 2 ± 3%, 71 ± 7%, and 27 ± 7%, respectively. In men, the mean ± SD percent time spent at low, moderate, high, and maximal intensities from measures of power
Figure 2-6. The mean (±SD) percent time spent at low (> 50% of VO₂ peak), moderate (50-70%), high (70-90%), and maximal (> 90%) intensities during the prologue in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
Figure 2-7. The mean (±SD) percent time spent at low (> 50% of VO₂ peak), moderate (50-70%), high (70-90%), and maximal (> 90%) intensities during the criterium in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
was 38 ± 3%, 11 ± 1%, 12 ± 1% and 39 ± 1%, respectively, while the percentages from heart rate was 0 ± 0%, 3 ± 4%, 67 ± 11% and 30 ± 11%, respectively. Graphical results for the criterium are presented in Figure 2-8.

Heart Rate vs. Power in the Laboratory and Field:

In the laboratory, significant and linear correlations were found between heart rate and power output, \( r = 0.995 \pm 0.004, p < 0.001 \). For the men, the average (± SD) slope and intercept describing heart rate from power output was 0.32 ± 0.05 and 63 ± 16, respectively (Heart rate = slope × power output + intercept). For women, the average (±SD) slope and intercept was 0.41 ± 0.06 and 64 ± 14, respectively. While significant difference was found in the slope between men and women, no difference was found in the intercept.

In the field, the relationship between heart rate and power output was significantly affected by the time frame used to average the heart rate and power data. When the relationship between heart rate and power output was assessed with the original time interval that was used to record the data (1 to 3 seconds), no significant relationship was found between heart rate and power output using linear regression. When the relationship was assessed by taking the average heart rate and power output for 1 minute in the prologue and 5 minutes for the circuit/road races and criterium, significant correlations were found in the circuit/road races in men and women, but not in the prologue or criterium in men or women.

For a data recording interval of 1 to 3 seconds, the mean (± SD) slope between heart rate and power output for the prologue, circuit/road races, and criterium was –
Figure 2-8. The mean (±SD) percent time spent at low (> 50% of VO₂ peak), moderate (50-70%), high (70-90%), and maximal (> 90%) intensities during the criterium in women and men calculated using either power output or heart rate.
* Significantly different from heart rate (p < 0.05).
0.007 ± 0.002, 0.025 ± 0.19, and 0.001 ± 0.007, respectively in the men and - 0.015 ± 0.008, 0.049 ± 0.025, and - 0.003 ± 0.002, respectively in the women. For the same recording interval, the mean (± SD) intercept for the prologue, circuit/road races, and criterium was 179 ± 8, 150 ± 10, and 164 ± 5, respectively in the men and 178 ± 12, 141 ± 8, and 166 ± 8, respectively in the women. No significant difference was found between men and women except in the slope during the prologue and circuit/road races, and in the intercept of the circuit road races. In the men, significant difference was found in the slope between the prologue versus circuit/road races and between the circuit/road races versus the criterium, with no difference between the prologue and criterium. Significant difference was also found in the intercept between the prologue versus circuit/road races, prologue versus criterium, and circuit/road races versus criterium. In the women, significant difference was found in the slope and intercept between the prologue versus circuit/road races, prologue versus criterium, and circuit/road races versus criterium.

For a data recording interval of 1 or 5 minutes, the mean (± SD) slope between heart rate and power output for the prologue, circuit/road races, and criterium was - 0.013 ± 0.006, 0.17 ± 0.05, and 0.11 ± 0.05, respectively in the men and - 0.025 ± 0.019, 0.28 ± 0.07 ± 0.07, and 0.09 ± 0.02, respectively in the women. The mean (± SD) intercept for a recording interval of 1 or 5 minutes in the prologue, circuit/road races, and criterium was 183 ± 8, 115 ± 13, and 135 ± 17, respectively in the men and 182 ± 14, 104 ± 9, and 148 ± 12, respectively in the women. No significant difference was found between men and women except in the slope during the prologue and circuit/road races. In the men, significant difference was found in
the slope and intercept between the prologue versus circuit/road races, prologue versus criterium, and circuit/road races versus the criterium. In the women, significant difference was found in the slope and intercept between the prologue versus circuit/road races, prologue versus criterium, and circuit/road races versus criterium.

Table 2-6 lists the mean (± SD) slopes, intercepts, and Pearson r values describing heart rate from power output using linear regression. These values are given for the original recording interval (1 to 3 seconds) as well as a 1-minute time average for the prologue and 5-minute time average for the circuit/road races and criterium in both the men and women. In addition to these values, the standard error of estimate was calculated for each individual linear regression describing heart rate from power and power from heart rate. The mean (±SD), minimum, and maximum values for the standard error of estimate for heart rate from power (HR) and power from heart rate (Power) are listed in table 2-7.

Figure 2-9 and 2-10 are graphical representations of the heart rate versus power output relationship in men and women during the laboratory GXT, prologue, circuit/road races, and criterium. In figure 2-9, the data for the race events are generated using 1 to 3 second time intervals, while in figure 2-10, the data is generated using 1 to 5 minute time intervals. This same relationship is also displayed for two single subjects for each of the six events in figure 2-11 using a 1 to 5 minute time interval.

In figure 2-12, 2-13, and 2-14 a graphical representation of the heart rate versus power output relationship relative to time is displayed for a single individual
Table 2-6. The slope, intercept, and pearson r value describing heart rate (y) from power output (x) using best fit linear regressions during the laboratory GXT, prologue, circuit/road races, and criterium in men and women. Two distinct recording intervals were used for these values. The first is the original recording interval ranging from 1 to 2 seconds, while the second is a 1-minute average used during the GXT and prologue or a 5-minute average used during the circuit/road races and criterium.
<table>
<thead>
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<th>Rec Int</th>
<th>GXT</th>
<th>Prologue</th>
<th>Circuit / RR</th>
<th>Criterium</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 3 sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
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<td>-0.007 ± 0.002</td>
<td>0.025 ± 0.019</td>
<td>0.001 ± 0.007</td>
</tr>
<tr>
<td>Int</td>
<td>-</td>
<td>179 ± 8</td>
<td>150 ± 10</td>
<td>164 ± 5</td>
</tr>
<tr>
<td>r</td>
<td>-</td>
<td>-0.15 ± 0.05</td>
<td>0.25 ± 0.13</td>
<td>0.11 ± 0.11</td>
</tr>
<tr>
<td>1 or 5 min</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.32 ± 0.05</td>
<td>-0.013 ± 0.006</td>
<td>0.17 ± 0.05</td>
<td>0.11 ± 0.05</td>
</tr>
<tr>
<td>Int</td>
<td>63 ± 16</td>
<td>183 ± 8</td>
<td>115 ± 13</td>
<td>135 ± 17</td>
</tr>
<tr>
<td>r</td>
<td>0.994 ± 0.005</td>
<td>-0.25 ± 0.14</td>
<td>0.79 ± 0.17</td>
<td>0.51 ± 0.08</td>
</tr>
<tr>
<td>1 to 3 sec</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>-</td>
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<td>0.049 ± 0.025</td>
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</tr>
<tr>
<td>Int</td>
<td>-</td>
<td>178 ± 12</td>
<td>141 ± 8</td>
<td>166 ± 8</td>
</tr>
<tr>
<td>r</td>
<td>-</td>
<td>-0.24 ± 0.11</td>
<td>0.32 ± 0.09</td>
<td>-0.06 ± 0.04</td>
</tr>
<tr>
<td>1 or 5 min</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>0.44 ± 0.06</td>
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<td>0.28 ± 0.07</td>
<td>0.09 ± 0.02</td>
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<tr>
<td>Int</td>
<td>64 ± 14</td>
<td>182 ± 14</td>
<td>104 ± 9</td>
<td>148 ± 12</td>
</tr>
<tr>
<td>r</td>
<td>0.996 ± 0.003</td>
<td>-0.32 ± 0.31</td>
<td>0.88 ± 0.04</td>
<td>0.47 ± 0.10</td>
</tr>
</tbody>
</table>

* Significantly different from 1 or 5 min recording interval
† Significantly different from men
∞ Significantly different from prologue
¥ Significantly different from circuit/road races
§ Significantly different from criterium
Table 2-7. The mean (± SD), minimum (min), and maximum (max) standard error of estimate for the individual linear regressions describing heart rate from power output (HR) and power output from heart rate (Power) using data averaged over a 1 minute (prologue) or 5 minute period of time (circuit/road races and criterium).
<table>
<thead>
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<th>Criterium</th>
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<tbody>
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<td></td>
<td>HR</td>
<td>Power</td>
<td>HR</td>
</tr>
<tr>
<td><strong>M</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.0 ± 1.1</td>
<td>85 ± 6</td>
<td>7.8 ± 2.1</td>
</tr>
<tr>
<td>Min</td>
<td>3.5</td>
<td>74</td>
<td>4.9</td>
</tr>
<tr>
<td>Max</td>
<td>6.2</td>
<td>90</td>
<td>13.0</td>
</tr>
<tr>
<td><strong>W</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.1 ± 1.7</td>
<td>57 ± 14</td>
<td>7.0 ± 1.5</td>
</tr>
<tr>
<td>Min</td>
<td>2.3</td>
<td>40</td>
<td>4.6</td>
</tr>
<tr>
<td>Max</td>
<td>5.2</td>
<td>89</td>
<td>11.5</td>
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</table>

**Table:**

<table>
<thead>
<tr>
<th><strong>M</strong></th>
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<th>Circuit/Road Races</th>
<th>Criterium</th>
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</thead>
<tbody>
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<td>85 ± 6</td>
<td>7.8 ± 2.1</td>
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<td>13.0</td>
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<tr>
<td><strong>W</strong></td>
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<td></td>
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</tr>
<tr>
<td>Mean</td>
<td>4.1 ± 1.7</td>
<td>57 ± 14</td>
<td>7.0 ± 1.5</td>
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<tr>
<td>Min</td>
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<td>89</td>
<td>11.5</td>
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</table>
Figure 2-9. Mean ± SD regression plots relating heart rate and power output from the laboratory GXT, the prologue, circuit/road races, and criterium with data averaged in a time interval of 1 to 3 seconds. A significant and linear relationship was found in the GXT, but not in any of the races.
Figure 2-10. Mean ± SD regression plots relating heart rate and power output from the laboratory GXT, the prologue, circuit/road races, and criterium with data averaged in a time interval of 1 to 5 minutes. Significant correlations were found in the circuit/road races in men and women, but not in the prologue or criterium in men or women.
Figure 2-11. The relationship between heart rate versus power output using the linear regression established with data averaged in 1-minute increments during the prologue and 5 minute increments in the remaining 5 events. Data is given for two single individuals.
Figure 2-12. A) Sample heart rate vs. power output relationship in a single subject during the prologue using data recorded in 1 to 3 second increments. B) Heart rate vs. power using data averaged every minute. C) Heart rate and power output vs. time using data recorded in 1 to 3 second increments. D) Heart rate and power output vs. time using data recorded averaged every minute.
A. 

Heart Rate (bpm) vs. Power (watts)

HR = 0.009 x Power + 175, r = -0.18

B. 

Heart Rate (bpm) vs. Power (watts)

HR = -0.018 x Power + 180, r = -0.43

C. 

Power vs. Time (min)

Heart Rate vs. Power

D. 

Power vs. Time (min)

Heart Rate vs. Power
Figure 2-13. A) Sample heart rate vs. power output relationship in a single subject during the longest road race using data recorded in 1 to 3 second increments. B) Heart rate vs. power using data averaged every 5 minutes. C) Heart rate and power output vs. time using data recorded in 1 to 3 second increments. D) Heart rate and power output vs. time using data recorded averaged every 5 minutes.
A. 

![Graph A](image1)

B. 

![Graph B](image2)

C. 

![Graph C](image3)

D. 

![Graph D](image4)
Figure 2-14. A) Sample heart rate vs. power output relationship in a single subject during the criterium using data recorded in 1 to 3 second increments. B) Heart rate vs. power using data averaged every 5 minutes. C) Heart rate and power output vs. time using data recorded in 1 to 3 second increments. D) Heart rate and power output vs. time using data recorded averaged every 5 minutes.
during the prologue, the longest road race, and criterium. The data is displayed using both 1 to 3 second time intervals and 1 to 5 minute time intervals.

**Discussion**

Although there is a strong relationship between heart rate and power output during graded exercise in the laboratory, we observed a significant dissociation between heart rate and the real time pattern of power output in the field. As a result, heart rate cannot be used to predict the average power output, energy expenditure, or distribution of power output during competitive road cycling events. Because the heart rate response can be affected by more than just the power output, heart rate may still be indicative of the overall cardiovascular demands, but should not be thought of as synonymous with the metabolic or physical demands placed on skeletal muscle, especially in non-steady state events. Thus, previous studies that have used field-based measures of heart rate to describe the demands of competitive road cycling should be interpreted with caution.

We selected this particular stage race primarily because it is, to our knowledge, the only professional race where men and women compete over the same courses and distances. These distances were similar to World Cup events for women (43), but about 50 to 75% shorter than normally faced by professional men (39, 42, 47). Despite this limitation, we found the opportunity to compare both genders under equivalent race distances to be unique and important. Based on our laboratory results, our men and women are as fit as other elite or nationally competitive cyclists of the same gender (52, 68), but not as fit as professional men and women competing at the
highest international level (39, 42, 43, 47). Though men had faster finishing times and higher absolute power outputs, no significant difference was found between men and women in their relative power or heart rate response. Thus, the following discussion applies to both men and women unless specifically noted.

Because laboratory testing occurred at a moderate altitude while the racing occurred close to sea level, it could be argued that the heart rate-power regression we used for data analysis is not specific to the field (63). While it is true that exposure to high altitude can elevate the submaximal heart rate response (44, 65), given the sigmoidal shape of the oxyhemoglobin dissociation curve, our moderate elevation would, theoretically, not be enough to change submaximal oxyhemoglobin saturation and should not have affected our laboratory heart rate response. To test this hypothesis, we assessed the relationship between heart rate and power output during a laboratory GXT in a group of highly trained amateur male cyclists (n = 8, VO₂ peak = 64.23 ± 4.13 ml·kg⁻¹·min⁻¹) during exposure to room air at moderate altitude (pb = 629.6 ± 3.1 mmHg, F₁O₂ = 0.2094) and exposure to a hyperoxic gas at the same elevation to simulate sea level (pb = 629.8 ± 2.5 mmHg, F₁O₂ = 0.25). No difference was found in the slope (p = 0.23) or intercept (p = 0.89) of the heart rate versus power output relationship between moderate altitude (slope = 0.32 ± 0.05, intercept = 66.9 ± 11.8, r = 0.996 ± 0.00, p < 0.001) and simulated sea level (slope = 0.29 ± 0.03, intercept = 67.3 ± 11.8, r = 0.997 ± 0.004, p < 0.001). Thus, we do not believe that testing subjects in our laboratory significantly altered the baseline heart rate vs. power output relationship used in data analysis. This finding, however, is moot given the fact that if exposure to a moderate altitude did raise the heart rate response at a given
submaximal power output, then heart rate would have under-predicted power output at sea level. Because we found heart rate to actually over-estimate the power output in the circuit/road races and criterium any under-prediction would have decreased the actual difference between power and heart rate, blunting, not accentuating our observed results. Accordingly, our findings, at worst, could be thought of as conservative.

As hypothesized, compared to the actual power output, heart rate significantly underestimated average power by -47 watts (-13.5%) during the prologue while overestimating average power by 37 watts (18.5%) and 35 watts (14.8%) in the circuit/road races and criterium, respectively. These differences bring into question the common use of a laboratory based heart rate-power regression to extrapolate the physical or metabolic demands of competitive cycling from field measures of heart rate. Although, there is evidence that there is no relationship between heart rate and power output in the field, almost our entire knowledge base regarding the demands of competitive cycling is derived from heart rate, and from the basic assumption that the relationship between heart rate, power, and other physiological responses during graded exercise in the laboratory is the same in the field (9, 19, 21, 38, 43, 49, 50, 52, 53).

Compared to these studies, our mean heart rate responses are similar. For example, Palmer et al., described a mean heart rate response (69% of VO₂ peak) in two road races that was nearly identical to the mean heart rate response for our men in circuit/road races (70% of VO₂ peak) of comparable durations (52). If we, however, assume the same dissociation between heart rate and power, the actual relative
intensity of the road races monitored by Palmer et al., could be 10 to 30% lower than previously thought. While it is unknown if this also holds true in professional men competing in significantly longer events (> 4 hrs) at lower mean heart rate values (50 to 60% of VO₂ peak) (19, 38, 50), given the non-steady state nature of these events, there would be no reason to suspect otherwise (9). This is especially true, since we found the absolute and relative dissociation between power and heart rate to be similar across a broad time frame (1 to 5 hrs) and heart rate intensity range (50 to 90% of VO₂ peak). Compared to other prologue data of comparable durations, the mean heart rate response in our study (92.5%) was similar (49). Based on our field data and laboratory data examining supra-maximal and maximal efforts of this duration, it is likely that heart rate underestimates the mean power for prologue events in the field (2). Accordingly, we believe that in studies describing the average intensity of competitive cycling events using heart rate, that the average power is underestimated by 10 to 15% in very short events (<10 minutes) and overestimated by 15 to 20% in long events (1 to 5 hrs).

While there are many potential explanations for the dissociation between power and heart rate, a significant portion may be due to the inherent lag in heart rate response to a non-steady state pattern of power (3, 9, 43, 53). As an example of the variability in power, it is valuable to note that the standard deviation in power output was equivalent to 77 (± 7.7)% (men: 186 ± 20 watts; women: 148 ± 7.8 watts) and 79 (± 3.2)% (221 ± 3.1 watts; women: 160 ± 16 watts) of the mean power output measured during the circuit/road races and criterium, respectively. This was significantly greater than the standard deviation in heart rate, which ranged from only
5 to 12% of the mean heart rate during the same events. By itself, this result
demonstrates the fundamental difference in the pattern of power output relative to
heart rate and is a critical aspect of the dissociation between these variables. As a
result, at the original sampling interval of 1 to 3 seconds we found no correlation
between heart rate and power output in any event. While using a sampling interval of
5-minutes significantly improved the correlation in the circuit/road races and
criterium, the correlation between heart rate and power in these events \( r = 0.47 \) to
0.88) never approached that found in the laboratory \( r > 0.99 \). In fact, even with this
longer time period, based on the standard error of estimate, at any given heart rate,
power varied by an average of 65 watts during the circuit/road races and 95 watts
during the criterium. More importantly, regardless of the time interval used to smooth
the data, significant differences were found in the slope and intercept of the heart rate
versus power relationship, not only between the field and laboratory, but also between
the different field events. Thus, even if the correlation between heart rate and power
in the field was perfect, neither laboratory nor field based regressions could be used
to accurately predict power from heart rate. As a result, studies that attempt to
compare variable events over stage races lasting up to three weeks with a single
laboratory heart rate-power regression are inherently flawed (19, 38, 50). This is
especially true, since over consecutive days of intensified or prolonged training, heart
rate has been shown to decrease at a given submaximal power output or \( \text{VO}_2 \) (6, 46).

Beyond the lag in heart rate response, other factors may have affected the
heart rate response at a given power output. For example, during prolonged exercise
in the heat, the combined effect of dehydration and competition for peripheral blood
flow to maintain thermoregulation can increase the heart rate response by more than 20 beats per minute (bpm) at a given power output (13, 24, 28, 58). In addition, during high intensity intermittent exercise or sustained high intensity exercise, there is an associated drift in oxygen cost or an excess post oxygen consumption, which all things being equal could result in an increase in heart rate of 10 to 15 bpm (4, 35, 70). Heart rate could also have become disproportionately elevated by direct neural input stimulated by an athlete’s personal response to external race events, or humorally by an increase in circulating catecholamines (10, 48, 57, 69). Finally, some researchers have shown that acute and/or chronic fatigue is associated with an increase in both the resting and submaximal heart rate response (1, 23).

The error in mean power calculated from heart rate also creates significant errors in the calculated energy expenditure. Using the gross mechanical efficiency (GME) measured for each subject and assuming that this value did not change while competing, heart rate mispredicted energy expenditure in our subjects by -230 ± 101 kcsals·hr⁻¹ in the prologue, (men: -258 ± 127 kcsals·hr⁻¹; women: -204 ± 86 kcsals·hr⁻¹), 152 ± 87 kcsals·hr⁻¹ over the circuit road races (men: 160 ± 112 kcsals·hr⁻¹; women: 144 ± 60 kcsals·hr⁻¹), and by 133 ± 41 kcsals·hr⁻¹ in the criterium (men: 145 ± 48 kcsals·hr⁻¹; women: 121 ± 35 kcsals·hr⁻¹). In a typical professional men’s road race of 5 hours, this would be equal to an absolute difference of 720 kcsals. This is a significant difference that has important implications. As an example, in a simulation of the Tour de France, the laboratory exercise intensity was entirely based on data from heart rate measures in the field. As a result, the calculated energy costs were so great that with solid food, subjects could not adequately replace the required energy intake. Because, heart rate
overestimates the caloric demand, whether this simulation is an accurate reflection of actual practices while racing is suspect (11, 12, 59).

Theoretically, however, there may be some controversy as to whether power or heart rate provides a more accurate estimate of energy expenditure. While power can account for energy production from both anaerobic and aerobic sources, it cannot account for oxygen consumption in excess of any oxygen deficit. At the same time, a drift in oxygen cost may elevate heart rate, but heart rate cannot directly measure energy from anaerobic sources and may be excessively elevated during pauses in power. While it is unknown if these limitations offset one another, it is known is that whole body post exercise oxygen consumption is normally in excess of the oxygen deficit (4). Accordingly, it is likely that average power, despite accounting for the energy cost of supra-maximal efforts, underestimates the total body energy expenditure. Alternatively, for all of the energy overestimated by heart rate to be caused by a drift in oxygen consumption, the mean GME of our subjects would have to decrease by 3% from a mean of 22% to 19%. For some subjects who had heart rate responses that overestimated energy expenditure by over 300 kcal·hr⁻¹, GME would have to drop by more than 5%. To our knowledge there are no reports that GME could change this much during a bout of sustained stead state or high intensity intermittent exercise. More importantly, based on the variability we observed in the heart rate vs. power regression within and between race events, it is likely that the relationship between heart rate and oxygen consumption is significantly more variable than economy. Thus, we believe that power is a far more reliable measure of energy expenditure than heart rate.
Based on these factors and our findings, it is clear that heart rate cannot be used to describe the average power output or energy expenditure during competitive cycling. More importantly, it could be argued that average intensity or total work tells us very little about the overall demands of a given event. Accordingly, most heart rate monitoring studies also examine the distribution of exercise intensity relative to some physiological reference such as the lactate threshold or VO\(_2\) max (19, 38-40, 43, 49, 50). As an example, Fernandez-Garcia et al., monitored the heart rate response of 18 professional cyclists during the Tour de France (138 stages) and Vuelta (134 stages), examining the distribution of power output over four distinct intensity ranges. Based on heart rate, these professional cyclists spend an average of 25%, 32%, 30%, and 15% of their time at low (< 50% of VO\(_2\) max), moderate (50-70%), high (70-90%), and maximal (> 90%) intensities, respectively (19). In our present study, based on heart rate our cyclists spent 10.5%, 29.5%, 45.5%, and 14.5% at low, moderate, high, and maximal intensities during the circuit/road races. While our distributions for heart rate are similar, our cyclists did not spend as much relative time at low intensities and tended to spend more relative time at high intensities. Unfortunately, compared to power, heart rate significantly underestimated relative time at low intensities (44.5% by power), overestimated time at moderate (17%) and high (14.5%) intensities, and underestimated time at maximal (24.5%) intensities. More than likely, this same dissociation is generalizable to the cyclists studied by Fernandez-Garcia et al., which would mean that professional cyclists tend to spend more time at low and maximal intensities and less time at moderate and high intensities. From a training perspective, this might mean that for a given duration cyclists basing their training from heart rate
studies spend more time at or near the lactate threshold, while those basing their training from a power reference might spend more time at maximal or recovery intensities.

Of interest, Fernandez-Garcia et al., noted that based on heart rate their cyclists spent roughly 20 minutes at maximal intensities in road race stages regardless of stage type (flat vs. mountain) or duration, suggesting that there was some absolute limit of time that cyclists could spend at maximal intensities (19). Though it is difficult to directly compare these results to other studies, this trend does not seem to hold true in similar cyclists during other Grand Tour stage races (38, 50). Our findings, however, are similar to Fernandez-Garcia et al., despite race durations that were significantly shorter. Based on heart rate, our cyclists spent between 15 to 30 minutes at maximal intensities regardless of gender, event duration or type. In addition, time trial data from another study indicate that during uphill or level time trials of approximately 30 minutes, our cyclists spent, based on heart rate, 15 to 25 minutes above 90% of VO₂ max(37). While the notion of a fixed absolute time frame for work above 90% of VO₂ max is interesting, it is important to note, that the absolute time measured by power across events is not consistently related to the absolute time measured by heart rate. For example, in the circuit road race the actual time, based on power output, at maximal intensities averaged 43 minutes, while in the criterium the actual time averaged 25 minutes. Furthermore, in our 30-minute time trials, heart rate overestimated, rather than underestimated time at maximal intensities, with only 12.5 minutes spent at maximal intensities. Thus, the actual amount of time spent at maximal intensities seems related to the total duration, with
more time spent at maximal intensities in longer events and less time in shorter events. This may be due to the fact that in longer events, there is more time to recover from maximal efforts and thus more time may be accumulated at maximal intensities. The fact, that professional cyclists competing in much longer events spend more relative and absolute time at low to moderate intensities compared to our subjects competing in shorter events seems to fit this idea (19, 38, 50). In fact, a basic principle of interval training is that more high intensity work can be done in an intermittent fashion than continuously (5, 7). Based on this, it is possible that professional cyclists spend far greater time at maximal intensities than previously thought. Scaling our heart rate-power dissociation to the duration of a typical Grand Tour stage, it is possible that up to 60 minutes of total time might be spent above 90% of VO₂ max power.

In an attempt to better explain why the absolute time at maximal intensities may stay relatively constant while the actual time is variable, we quantified the pattern by which maximal and supra-maximal time is accumulated by calculating the number of times subjects surged above 90% and 100% of VO₂ peak power as well as the average duration they stayed above this power output. Interestingly, there was no significant difference in the pattern between 90% and 100% of VO₂ peak power, indicating that when a subject surged above 90% of VO₂ peak power, they also surged past 100%. Accordingly, maximal efforts in our events were in effect supra-maximal efforts. In the circuit/road races, the men surged an average (±SD) of 252 (± 70) times above their VO₂ peak power, stayed above this power output for an average of 7.2 (± 2.4) seconds, with an average interval of 42 (± 22) seconds between each
surge. A similar pattern was also found in women during the circuit road/races (224 ± 64 surges, 7.3 ± 1.5 sec duration, 55 ± 16 sec interval), and in both genders during the criterium (men: 176 ± 37 surges, 6.8 ± 2.4 sec duration, 22 ± 5 sec interval; women: 190 ± 20.1 surges, 6.2 ± 0.4 sec duration, 22 ± 2.5 sec interval). In the criterium, however, the recovery interval was significantly shorter (22 seconds) than in the circuit road races (49 second) despite no significant difference in the average surge time. Due to the delay associated with heart rate response, the supra-maximal nature of these surges, and their short time frame (6-7 seconds), these frequent and sudden increases in power output would not be directly apparent through measures of heart rate, but could have contributed to an overall drift in the heart rate response. With almost twice the recovery time in the circuit/road races compared to the criterium, it is possible that the amount of drift in the circuit/road races was significantly lower, explaining why heart rate might indicate the same absolute time at maximal intensities for both types of events, when in fact, the total absolute time at supra-maximal intensities was significantly different.

Given the significant dissociation in the distribution of power and heart rate as well as the large variability in power output, the energy pathways and substrates utilized during competitive cycling are probably very different than previously assumed with measures of heart rate. In general, professional road cycling has been described as a low to moderate intensity sport that is highly dependent upon aerobic metabolism (19, 38, 39, 50). While these authors concede that anaerobic metabolism is also important given the time spent at near maximal intensities, the absolute time that we describe at these intensities is 2 to 3 times what has been described in the
literature. More importantly, based on the very short time frame that maximal and supra-maximal power outputs are applied, road cycling might be better characterized as a prolonged sprint session than as an ultra-endurance event. This is extremely important, since it has been shown that glycogen depletion during high intensity intermittent exercise or during repeated sprints, is significantly greater than during high intensity exercise performed in a steady state fashion (3, 56). This is probably due to the fact that glycogen is depleted more rapidly from fast (type IIa or b) muscle fibers than slow fibers (56). With over 30% of the total time during the circuit/road races and criterium spent at supra-maximal power outputs (> VO₂ peak power), the recruitment of fast fibers is significant, and much greater than predicted by heart rate (10 to 15% of total time above 90% of VO₂ peak). Thus, it is likely that the use of glycogen at actively recruited muscles is significantly greater during road cycling events than previously thought. This possibility essentially negates the finding that heart rate overestimates the total energy expenditure, since it could be argued that performance in road cycling is not limited by the maintenance of energy balance during a prolonged road event, but by the maintenance of muscle glycogen and/or exogenous carbohydrate (14, 15, 25, 27). Beyond, the limitation of substrate, evidence exists that mild dehydration while not limiting moderate intensity exercise (70%), significantly impairs high intensity (90% VO₂ max) exercise (64).

Because we do not have data on the subject’s dietary intake during or after the events and our steady state laboratory measures are not generalizable to the field, the actual metabolic demands faced by our subjects remain unknown. It is, however, evident that road cycling, which is normally thought of as an aerobic event because of
the duration and previous descriptions of intensity by heart rate, is equally dependent on anaerobic metabolism, raising questions about whether current training, nutrition, and testing strategies for competitive cyclists are truly specific or optimal. As an example, given the pattern of power output we observed, there is a strong rationale for the use of high intensity interval training for professional cyclists despite the long durations and low average intensity (51, 54, 61, 66, 67).

A more definitive problem associated with heart rate estimates of power are the significant errors that would arise using these values to model performance. For example, up an 8% grade, if we assume constants for gravitational, aerodynamic, and rolling resistance, the time differential modeled using the heart rate estimate of power (289 watts) and actual power (242 watts) from the men in the circuit/road races would be equal to over 9 minutes each hour (18). On the level, assuming the same constants for aerodynamic and rolling resistance, the time difference would be close to 4 minutes each hour (18). Essentially, on the level a 25 watt error in power amounts to a 1 to 2 minute time difference per hour between 300 and 400 watts, while the same range results in a 3 to 5 minute time difference per hour uphill. Since competitive cycling events can be won or lost be seconds and small changes in power can lead to large time differences, for the purpose of modeling cycling performance estimates of power from heart rate should be avoided.

Despite the problems inherent in heart rate monitoring, we do not believe that evaluating the heart rate response during competition is unimportant. On the contrary, some might argue that an individual’s response to an external stimulus is as important as the stimulus itself. In that sense, if heart rate were used as a physiological response
instead of a substitute for the actual stimulus, as it is in many studies describing
eexercise intensity, there would be a real and inherent value to heart rate monitoring.
This, of course, assumes that power can be easily and accurately measured in the
field. In the sport of cycling the technology is at a point where this assumption has
already become common practice amongst professional cyclists. Thus, an alternative
perspective is that we can learn more about performance by understanding the acute
and chronic relationship between power and heart rate, rather than viewing them as
either mutually exclusive or perfectly related. Accordingly, the dissociation observed
between power and heart rate in the field, raises important questions about how and if
the relationship between power and other physiological responses during competition
is also significantly affected. Because much of our understanding of performance in
cycling is still based on steady state or graded exercise in laboratory settings, it is
clear that we may have little understanding of the true acute responses or chronic
adaptations associated with competitive cycling. With the continued insight provided
by power and heart rate monitoring in the field and the appropriate technology, we
believe that future attempts can and should be made to simulating specific
competitive events in the laboratory to remedy this gap in knowledge.

In conclusion, heart rate and power provide different descriptions of
competitive cycling demands with respect to power output, energy expenditure, and
the distribution of power output. As a result, if possible heart rate should not be used
alone to describe the stimulus associated with competitive cycling. Moreover,
previous descriptions of the competitive demands of cycling by heart rate lack in
specificity and may not be optimal in understanding the training and testing needs of
competitive cyclists. Thus, further research is required to re-evaluate previous assumptions about cycling performance that are based on either steady state or graded exercise models.
References


CHAPTER IV: USE OF CYCLE MOUNTED POWER METERS TO
ESTIMATE THE AERODYNAMIC CHARACTER AND ROLLING
RESISTANCE OF ROAD CYCLISTS

Abstract

Purpose: To develop a protocol for isolating aerodynamic resistance per 
velocity squared and rolling resistance from field-based measures of power and 
velocity during level cycling. Methods: We assessed the effect of body position 
(hands on brake hoods vs. drops) and tire pressure changes (414 vs. 828 kPa) on 
aerodynamics and rolling resistance by measuring the power (P_{ext}, watts) vs. speed 
(V, m\cdot s^{-1}) relationship using commercially available rear hub (Power Tap®, Madison 
WI) and crank (SRM®, Julich Germany) mounted power meters. Measurements were 
taken while cycling on standard road bicycles in low wind (< 1.0 m\cdot s^{-1}) conditions at 
constant velocities (acceleration < 0.5 m\cdot s^{-2}) on a flat 200 m section of a smooth 
asphalt road. For each experimental condition, subjects rode from 100 to 300 watts 
for women (n=2) or 100 to 400 watts for men (n=6) in 50 watt increments. 
Aerodynamic resistance per velocity squared (k, N\cdot m^{-2}\cdot s^{2}) was calculated as the slope 
of a linear plot of tractive resistance (R_T = \frac{\text{power}}{\text{velocity}}, N) versus velocity squared. 
Rolling resistance (R_r, N) was calculated as the intercept of this relationship. Results: 
Aerodynamic resistance per velocity squared was significantly greater (p < 0.05) 
while riding in the brake hoods compared to the drops at both 60 psi (mean ± SD: 
0.18 ± 0.03 vs. 0.16 ± 0.03 N\cdot V^{-2}) and 120 psi (0.17 ± 0.02 vs. 0.15 ± 0.03 N\cdot V^{-2}) 
with no effect on k attributable to tire pressure. Rolling resistance was significantly
greater at 60 psi compared to 120 psi in the brake hoods (5.67 ± 0.78 vs. 4.29 ± 0.85 N) and drops (5.48 ± 0.61 vs. 4.14 ± 0.78 N) with no effect on Rᵣ attributable to position. Conclusions: These results demonstrate that commercially available power meters are sensitive enough to independently detect the changes in aerodynamic and rolling resistance associated with changes in body position and tire pressure.

Introduction

While cycling on level terrain at racing speeds (~40 km·hr⁻¹) about 90% of the resistance impeding forward motion is a result of aerodynamic resistance (Rₐ, N) with the remainder primarily a function of rolling resistance (Rᵣ, N) (8, 13, 16, 19, 21). Consequently, to predict level cycling performance, the power output or energy generating capacity of a given cyclist must be normalized primarily to some measure of that cyclist’s aerodynamic resistance. Investigators have employed many different techniques (e.g., wind tunnel, towing, deceleration measures, estimates from frontal area) to assess aerodynamic resistance during cycling, yet a single method has not been adopted on a broad scale. In addition, individual measures of aerodynamic resistance are not common in studies evaluating cycling performance (3, 4, 6-8, 12, 15, 16, 18, 21). Rather, aerodynamic resistance is simply assumed from previously established references or from estimates of projected frontal area, despite the large variability in aerodynamic resistance between different individuals, body positions, and equipment (1, 17, 19, 20). Thus, an accessible and accurate technique to assess an individual’s true aerodynamic resistance is needed.

A potential technique for this assessment may be the use of rear hub (Cycleops Power Tap®) or crank (SRM®) power meters that can measure external
power output ($P_{EXT}$, Watts) and ground velocity ($V$, m·s$^{-1}$) on a standard racing bicycle. In fact, Candau et al, have criticized previous measures of aerodynamic drag from wind tunnel, towing, and regression analysis, due to their complexity and lack of specificity, suggesting that cycle mounted power meters may be a solution to assessing drag during actual cycling (3).

If power output (Watts) and velocity (m·s$^{-1}$) are known then the total resistance to movement ($R_{TOT}$, N) can be calculated as power output divided by over-ground velocity.

1. $R_{TOT} = \frac{P_{EXT}}{V}$

Assuming that power is measured at the rear hub, that a cyclist is riding at a constant velocity on flat terrain, and that there is no wind, then $R_{TOT}$ is simply equal to aerodynamic resistance (N) plus rolling resistance (N). Under these conditions $R_{TOT}$ has been termed “Tractive Resistance” ($R_{Tr}$, N) (4, 5, 8, 21, 22).

2. $R_{Tr} = \frac{P_{EXT}}{V} = R_a + R_r$

Aerodynamic resistance is a function of velocity squared (m$^2$·s$^{-2}$), the air density ($\rho$, kg·m$^{-3}$), the projected frontal area of the bicycle and rider ($A_F$, m$^2$), and a coefficient, referred to as the drag coefficient ($C_D$, dimensionless) that is influenced by the shape of the bicycle and rider.

3. $R_a = 0.5\rho A_F C_D V^2$

If a constant ($k$, N·m$^2$·s$^2$) is used to represent the air density, projected frontal area, and the drag coefficient, then aerodynamic resistance can simply be expressed as:
(4) \( R_a = k \cdot V^2 \)

Substituting \( R_a \) with \( k \cdot V^2 \) yields the following equation for tractive resistance:

(5) \( R_T_r = P_{EXT} + V = k \cdot V^2 + R_r \)

Equation 5 is of the form of a linear regression equation where \( y = mx + b \).

Power output divided by speed is equal to \( y \), velocity squared is equal to \( x \), the slope or \( m \) is equal to the constant \( k \), and the intercept, \( b \), is equal to rolling resistance.

(6) \( y [P_{EXT} + V] = m [k] \cdot x [V^2] + b [R_r] \)

Accordingly, if external power output and velocity can be measured while cycling on level terrain at a constant velocity with no external wind, then a cyclist’s aerodynamic profile, measured as the constant \( k \) (i.e., the product of force per velocity squared, \( N \cdot m^{-2} \cdot s^{-2} \)), and rolling resistance, measured as a force (N), can be calculated.

Because \( k \) represents the air density, projected frontal area, and drag coefficient of the bicycle and rider, the aerodynamic profile of a given cyclist can be further reduced to a term that is independent of the environment if the air density is known.

(7) \( k = 0.5 \rho \cdot A_p \cdot C_D \)

The product of projected frontal area and drag coefficient of bicycle and rider has been termed the effective frontal area or “drag area” \( (A_d) \) (6, 10-12, 16, 21).

(8) \( k = 0.5 \rho \cdot A_d \)

Accordingly, dividing \( k \) by one-half the air density gives us the drag area, which can be used to describe a cyclist’s aerodynamic profile independent of the environment.
Likewise, rolling resistance is dependent upon the mass of the bicycle and rider system (mass, kg), the acceleration of gravity (g, m·s⁻²), and a coefficient (Cᵣ, unit-less) describing the tire quality (e.g., size, casing construction, and tread material/pattern) and road surface – a coefficient that is largely determined by tire pressure (9). By dividing rolling resistance by mass and the acceleration of gravity, rolling resistance can be expressed as a rolling coefficient (dimensionless) that is independent of mass and gravity. An overview of these relationships is presented in figure 1.

(10) $Cᵣ = \frac{Rᵣ - r}{\text{mass} \cdot g}$

Using this technique, Grappe et al., assessed aerodynamic resistance during actual field cycling using the MaxOne® (Look, France) rear hub power meter (10). Although, they found the MaxOne capable of discerning distinct body positions, they performed trials on only a single individual. In addition, the MaxOne is no longer manufactured and while its measure of power did correlate with their reference measure of power, the slope and intercept of those values did not agree. Consequently, it remains to be seen if a reliable and practical means of assessing an individual’s aerodynamic resistance can be developed using today’s new generation of portable power meters. Such a technique could be extremely valuable in helping athletes, coaches, and scientists to predict and improve cycling performance.
Figure 3-1. The diagram above details the calculation of aerodynamic resistance ($R_a$, N) and rolling resistance ($R_r$, N) from measures of external power ($P_{ext}$, watts) and over-ground velocity ($V$, m·s$^{-1}$). By taking distinct measures of $P_{ext}$ and $V$ at the rear wheel while cycling at a steady speed on level terrain in windless conditions, then a cyclist’s aerodynamic character, represented as $k$, can be calculated as the slope of the relationship between tractive resistance ($y$, $P_{ext}/V$) and velocity squared ($x$, $V^2$), while $R_r$ can be calculated as the intercept of this relationship. In this case, $k$ represents all of the primary determinants of aerodynamic resistance independent of the velocity and is equivalent to a force per velocity squared (N·m$^{-2}$·s$^{-2}$). If air density is known, then $k$ can be further reduced to the drag area ($A_d$, m$^2$), a value that describes aerodynamics independent of the environment. Finally, if $R_r$ is divided by the total mass of the bicycle and rider system (mass) and the acceleration of gravity (g) a rolling coefficient describing the quality of the tire and road interface can be calculated.
\[
\frac{\text{Power} (P_{\text{tot}})}{\text{Velocity} (V)} = \text{Total Resistance} (R_{\text{tot}}) = \text{Tractive Resistance} (R_{\text{tr}}) \text{ if: Level, no wind, & no acceleration}
\]

\[
R_{\text{tr}} = \text{Aerodynamic Resistance} (R_a) + \text{Rolling Resistance} (R_r)
\]

\[
R_a = 0.5 \cdot \text{Air Density} (\rho) \cdot \text{Projected Frontal Area} (A_p) \cdot \text{Drag Coefficient} (C_d) \cdot \text{Velocity} (V)^2
\]

\[
\text{Drag Area} (A_d) = A_p \cdot C_d
\]

\[
k = 0.5 \cdot \rho \cdot A_p \cdot C_d
\]

\[
R_{\text{tr}} = (k \cdot V^2) + R_r
\]

\[
R_r = \text{mass} \cdot g \cdot \text{Rolling Coefficient} (C_r)
\]

\[
y = \text{slope} \cdot x + \text{intercept}
\]
**Purpose**

To utilize the Power Tap and SRM power meters to measure aerodynamic resistance per velocity squared \((k)\) and drag area \((A_d)\) as well as rolling resistance \((R_r)\) and the rolling coefficient \((C_r)\) of individual cyclists riding on level terrain in distinct body positions and tire pressures.

**Hypothesis**

We hypothesized that at a constant tire pressure a change in body position would alter measures of \(k\) and \(A_d\) but not \(R_r\) or \(C_r\) and that in a single body position alterations in tire pressure would alter measures of \(R_r\) and \(C_r\) without changing measures of \(k\) or \(A_d\).

**Methods**

**Subjects**

Ten subjects, male \((n=7)\) and female \((n=3)\), were recruited for this study. All were experienced road cyclists actively competing as triathletes \((n=3)\) or road cyclists \((n=7)\), at the professional \((n=7)\) or elite amateur \((n=3)\) level. At the end of the study, however, data from only eight subjects met the appropriate criteria for inclusion in data analysis with only six of those eight completing all trials. The Human Research Committee at the University of Colorado at Boulder approved the protocol used for this study.

**General protocol**

Subjects cycled over a level section of road extending along an east-west axis, adjacent to the Boulder Airfield, termed the collection trap (CT). The CT consisted of
a section of road stretching 200, flanked at either end by “acceleration distances” of 400 to 500 m. The surface of the CT was comprised entirely of smooth black asphalt. The gradient of the CT was flat with a slight roll over the course that did not vary by more than 0.135° or 0.03%.

Four experimental conditions were determined using a combination of two body positions and two tire pressures. The two body positions were determined by the location of the subject’s hands and included 1) Hoods – seated with hands on the brake hoods and 2) Drops – seated with hands on the bottom section of the handlebars. Based upon each subject’s personal preference and riding experience the body positions for the two hand locations were determined. Once established, each individual was required to hold the same body position throughout all conditions. The two tire pressures used were 120 psi (828 kPa) and 60 psi (414 kPa). Accordingly, the four experimental conditions were, 1) Hoods at 120 psi, 2) Drops at 120 psi, 3) Hoods at 60 psi, and 4) Drops at 60 psi.

All tires were inflated to the required pressure with athletes sitting on their bicycles to remove the influence of individual body mass on tire pressure. In addition, all subjects were encouraged to maintain as consistent of a body position as possible while in the hoods or drops.

For each of the four experimental conditions, subjects were asked to ride in both directions (east and west) along the CT at a power output that ranged from 100 to 300 W for women and from 100 to 400 W for men at 50 W increments. At the end of a given pass in one direction, subjects ceased pedaling for 20 to 50 m after the end of the CT. This denoted the end of the CT in the data downloaded from the on-board
computer associated with each subject’s power meter. A given power output in a single direction was considered a trial while the average of both directions was considered a trial doublet. Men performed 7 trial doublets for each experimental condition while women performed 5 trial doublets for each experimental condition.

**Devices and Calibration**

All subjects utilized either the Power Tap (n=8) or SRM (n=2) power measuring devices, both of which record concurrent measures of the subject’s external power output and ground velocity. This data was stored to an onboard computer and downloaded after the completion of all experimental conditions for analysis.

Prior to commencing trials all units used during testing were calibrated against a zero torque reference while pedals were stationary and unloaded as directed by the manufacturer.

For the calculation of ground velocity, wheel circumference was initially measured directly with riders atop inflated tires but later standardized to a value of 2096 mm for the corresponding combination of rim diameter (622 mm) and tire height (≈ 23 mm) found with the 700 C rims and 23 mm “clincher” tires used by all subjects. This standardization stemmed from the finding that the maximum discrepancy between the circumference value of 2096 mm and that measured was only 10 mm (~ 0.5%) – a range that was within the sensitivity of our ability to measure velocity.

Using an external torque dynamometer we have demonstrated that the Power Tap and SRM are reliable and valid measures of power output (14, 23). The offset
between the two units, attributable to frictional losses in the drive train, remained constant at \(-7.6 \pm 2.5\) Watts throughout a power range of 100 to 500 Watts. This value was used to correct the SRM measurements to a power output representative of power at the rear hub.

**Environmental Conditions**

To control for the effect of alterations in air density \((\rho, \text{kg.m}^{-3})\), continuous measures of ambient temperature \((T, \text{K})\), station (barometric) pressure \((P_s, \text{Pa})\), and relative humidity \((H_r, \%)\) were collected via a Vantage Pro model weather instrument (Digital Instruments, Enterprise, OR). Air density was calculated using [need ref].

Additionally, instantaneous wind velocity was measured at discrete one-second intervals throughout all testing sessions by means of a hotwire anemometer (Extech Products Inc. Melrose, MA). To ensure for constant environmental conditions within subjects, each subject was required to complete all four experimental conditions in one test period – a time frame of 1 to 1.5 hours. All trials were completed in the early morning between 6 to 8 am when wind conditions are generally the calmest in Boulder, Colorado.

**Data Reduction and Analysis**

\(P_{\text{EXT}}\) and \(V\) were analyzed using Power Coach™ (Kochli Sport, Sonvilier, Switzerland) software operated by Apple G4 computers. This software presents data \((V, P_{\text{EXT}}, \text{Time, Distance})\) as discrete points representing averages of the recording interval specific to the device in use Power Tap (3 seconds), SRM (2 seconds). In analysing data from each trial, all points contributing to the 200 m distance preceding
the point at which subjects ceased pedalling ($P_{\text{EXT}} = 0$), were averaged for both $V$ and $P_{\text{EXT}}$. Additionally, the final data point (directly preceding $P_{\text{EXT}} = 0$) was always excluded so that trials in which subjects ceased pedalling at a time before the finish of the final 3-second average were not contaminated by an underestimate of the true $P_{\text{EXT}}$ value.

The $P_{\text{EXT}}$ and $V$ values achieved through this process were then averaged for the east and west directions to give a mean external power output and mean system velocity for each prescribed power output. No difference, however, was found between the mean measures for east trials compared to west trials. These mean values for $P_{\text{EXT}}$ and $V$ from the east and west trials comprised the data points used to assess tractive resistance.

Tractive resistance was calculated as power divided by velocity. A linear regression of tractive resistance versus velocity squared yielded a slope equal to aerodynamic resistance per velocity squared ($k$) and an intercept equal to rolling resistance. Drag area was calculated by dividing the aerodynamic drag by one-half air density. Finally, a coefficient for rolling resistance was calculated by dividing rolling resistance by the mass of the subject and bicycle system and the acceleration of gravity. Mass was measured for each subject and their bicycle using a balance scale (Detecto Scales, Webb City, MO).

**Exclusion Criteria**

Trials were excluded if:

1. Mean wind velocity exceeded 1.0 m·s$^{-1}$.
2. Acceleration exceeded 0.5 m·s$^{-2}$.
All exclusions were bi-directional, such that, if either trial (east or west) was determined unfit for further analysis, so too was the second trial of that pair. In the circumstance that three or more east-west data points were deleted from a single condition, the entire condition was removed from further statistical operations.

In the event that a subject did not complete all experimental conditions on a single test date, that subject’s data was also eliminated from analysis.

Of the 512 trial doublets scheduled for completion by 10 subjects (7 men and 3 women), 102 trial doublets (19.9%) were excluded or not completed. Only six subjects were able to complete all test conditions, 2 completed only the 120 psi condition in the hoods and drops, and 2 others were eliminated due to a combination of excessive wind and an inability to complete all test conditions.

Statistical Analyses

A 2 × 2 Repeated Measures Analysis of Variance was performed on a within subjects (n=6) basis to distinguish primary effects of body position and tire pressure on measures of k or drag area and rolling resistance.

The primary effects were further compared by paired, one-tailed, Student’s t-tests for the effect of tire pressure (n=6), and body position (n=8). Significance for all statistical analyses was set at a p-value less than 0.05.

Results

Individual, mean, and standard deviation data for aerodynamic resistance per velocity squared (k), rolling resistance (R_r), and the Pearson Product Moment
correlation coefficient for tractive resistance and velocity squared are presented in Table 3-1. Drag area ($A_d$), rolling coefficient ($C_r$), air density, and system mass (rider plus bicycle) are presented in Table 3-2.

For each subject and experimental condition the relationship between tractive resistance and velocity squared was linear and significant ($p < 0.05$) with a mean correlation coefficient for all trials > 0.99. At a given tire pressure, the slope of this relationship decreased significantly ($p < 0.05$) from the hoods to the drops, indicating a decrease in $k$. The intercept, however, did not change significantly at a given tire pressure between the hoods and drops, indicating a constant rolling resistance (Figure 3-2). In a given body position, slope did not change significantly, indicating a constant $k$. The intercept, however, increased significantly ($p < 0.05$) from 120 to 60 psi in a given position, demonstrating an increase in rolling resistance (Figure 3-3).

Moving from the hoods to the drops decreased $k$ from (mean ± SD) $0.1750 ± 0.0258 \text{ N} \cdot \text{m}^2 \cdot \text{s}^2$ to $0.1560 ± 0.0232 \text{ N} \cdot \text{m}^2 \cdot \text{s}^2$ at 120 psi and from $0.1765 ± 0.0290 \text{ N} \cdot \text{m}^2 \cdot \text{s}^2$ to $0.1574 ± 0.0280 \text{ N} \cdot \text{m}^2 \cdot \text{s}^2$ at 60 psi. Similarly, this position change decreased drag area from $0.3633 ± 0.0557 \text{ m}^2$ to $0.3238 ± 0.0510 \text{ m}^2$ at 120 psi and from $0.3659 ± 0.0626 \text{ m}^2$ to $0.3264 ± 0.0610 \text{ m}^2$ at 60 psi, a decrease of $11.45 ± 3.78\%$ and $10.90 ± 3.45\%$, respectively (Figure 3-4). While $k$ and drag area was significantly greater ($p < 0.05$) in the hoods compared to the drops at both 120 and 60 psi, no significant difference was found in $k$ or drag area in the hoods at 120 versus 60 psi or in the drops at 120 versus 60 psi.
Table 3-1. The individual and mean ± SD values for $k \ (N \cdot m^{-2} \cdot s^2)$ and rolling resistance (N) while riding in the hoods or drops at 120 psi and 60 psi. Significant difference ($p < 0.05$) was found in aerodynamic drag between body positions and rolling resistance between tire pressures. No difference ($p > 0.05$) was found in aerodynamic drag in a single body position between tire pressures or rolling resistance in a single tire pressure between body positions.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Aerodynamic Drag (N·m²·s⁻¹)</th>
<th>Rolling Resistance (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 psi</td>
<td>60 psi</td>
</tr>
<tr>
<td></td>
<td>Hoods</td>
<td>Drops</td>
</tr>
<tr>
<td>1</td>
<td>0.1921</td>
<td>0.1689</td>
</tr>
<tr>
<td>2</td>
<td>0.1614</td>
<td>0.1522</td>
</tr>
<tr>
<td>3</td>
<td>0.1450</td>
<td>0.1299</td>
</tr>
<tr>
<td>4</td>
<td>0.1544</td>
<td>0.1424</td>
</tr>
<tr>
<td>5</td>
<td>0.2218</td>
<td>0.2032</td>
</tr>
<tr>
<td>6</td>
<td>0.1939</td>
<td>0.1669</td>
</tr>
<tr>
<td>7</td>
<td>0.1579</td>
<td>0.1415</td>
</tr>
<tr>
<td>8</td>
<td>0.1736</td>
<td>0.1427</td>
</tr>
<tr>
<td>Mean</td>
<td>0.1750*</td>
<td>0.1560</td>
</tr>
<tr>
<td>SD</td>
<td>0.0258</td>
<td>0.0232</td>
</tr>
</tbody>
</table>

* Significantly different from drops at the same tire pressure.
† Significantly different from 60 psi in a given body position.
Table 3-2. The individual and mean ± SD drag area (m²), rolling coefficient, air density, and system mass while riding in the hoods or drops at 120 psi and 60 psi. Significant difference (p < 0.05) was found in drag area between body positions and rolling coefficient between tire pressures. No difference (p > 0.05) was found in drag area in a single body position between tire pressures or rolling resistance in a single tire pressure between body positions.
<table>
<thead>
<tr>
<th>Subject</th>
<th>Drag Area (m²)</th>
<th>Rolling Coefficient</th>
<th>Air Density (kg·m⁻³)</th>
<th>System Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 psi</td>
<td>60 psi</td>
<td>120 psi</td>
<td>60 psi</td>
</tr>
<tr>
<td></td>
<td>Hoods</td>
<td>Drops</td>
<td>Hoods</td>
<td>Drops</td>
</tr>
<tr>
<td>1</td>
<td>0.4025</td>
<td>0.3539</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.3341</td>
<td>0.3150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>0.3001</td>
<td>0.2689 0.3161</td>
<td>0.2894</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>0.3259</td>
<td>0.3055 0.3210</td>
<td>0.2925</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.4681</td>
<td>0.4289 0.4755</td>
<td>0.4398</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>0.3984</td>
<td>0.3429 0.4025</td>
<td>0.3536</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>0.3226</td>
<td>0.2891 0.3259</td>
<td>0.2883</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>0.3547</td>
<td>0.2916 0.3545</td>
<td>0.2946</td>
<td>-</td>
</tr>
<tr>
<td>Mean</td>
<td>0.3635*</td>
<td>0.3238 0.3659*</td>
<td>0.3264</td>
<td>0.0048†</td>
</tr>
<tr>
<td>SD</td>
<td>0.0557</td>
<td>0.0510 0.0626</td>
<td>0.0610</td>
<td>0.0009</td>
</tr>
</tbody>
</table>

* Significantly different from drops at the same time pressure.
† Significantly different from 60 psi in a given body position.
Figure 3-2. The relationship between $R_f$ (N) versus $V^2$ (m$^2$·s$^{-2}$) while riding in the Hoods and Drops at 120 psi for individual subjects and the mean for all subjects. For each subject, the slope between $R_f$ and $V^2$, decreased significantly from Hoods to the Drops, indicating a reduction in aerodynamic drag. At a single tire pressure, however, the intercept did not change, indicating no change in rolling resistance.
Tractive Resistance versus Velocity Squared:
Hoods versus Drops at 120 psi

![Graph showing tractive resistance versus velocity squared for hoods and drops at 120 psi.]
Figure 3-3. The relationship between $R_T$ (N) versus $V^2$ (m$^2$·s$^{-2}$), at 120 and 60 psi for individual subjects and the mean for all subjects. For each subject, the slope between $R_T$ and $V^2$ did not change between tire pressures, but the intercept increased significantly from 120 to 60 psi.
Tractive Resistance versus Velocity Squared:
120 psi versus 60 psi in Hoods

▲ Mean rolling resistance at 60 psi
▲ Mean rolling resistance at 120 psi
Figure 3-4. The drag area for individual subjects and the mean for all subjects while riding in the hoods and drops at 120 psi versus 60 psi. Drag area decreased significantly from the hoods to the drops at both 120 psi and 60 psi with no difference in drag area in a given position at either tire pressure.
Drag Area (m²) versus Position at 120 and 60 psi

* Significantly different from drops.
Decreasing tire pressure from 120 to 60 psi increased rolling resistance from 3.96 ± 0.94 to 5.67 ± 0.78 N while in the hoods and from 3.86 ± 0.90 to 5.48 ± 0.61 N while in the drops. Likewise, this decrease in tire pressure increased the rolling coefficient from 0.0048 ± 0.0009 to 0.0067 ± 0.0006 while in the hoods and from 0.0047 ± 0.0008 to 0.0065 ± 0.0005 while in the drops, an increase of 24.82 ± 7.02% and 24.83 ± 6.14%, respectively (Figure 3-5). Rolling resistance and rolling coefficient were significantly greater (p < 0.05) at 60 psi compared to 120 psi while in the hoods and drops position. No significant difference, however, was found between rolling resistance and rolling coefficient between body positions at 60 psi or at 120 psi.
Figure 3-5. The rolling coefficient for individual subjects and the mean for all subjects while riding in the hoods and drops at 120 versus 60 psi. No significant difference was found between the hoods and drops at a given tire pressure. Significant difference, however, was found between 120 psi versus 60 psi in both positions.
Rolling Coefficient versus Tire Pressure in the Hoods & Drops

† Significantly different from 60 psi.
Discussion

These results were consistent with our hypothesis that at a constant tire pressure a change in body position would alter measures of k and Aᵣ but not Rᵣ or Cᵣ and that in a single body position alterations in tire pressure would alter measures of Rᵣ and Cᵣ but not effect k or Aᵣ. While it may appear obvious that a change in tire pressure and body position would alter rolling resistance and a cyclist’s aerodynamic character, we have established that the combination of our protocol and power meters had the sensitivity to independently discern between changes in body position and tire pressure.

Many factors needed to be controlled for this protocol to be viable. These factors included 1) the ability of the rider to hold a constant velocity to eliminate inertial resistance, 2) the use of a level road to eliminate gravitational resistance, 3) the absence of an external wind so that ground velocity would equal relative air velocity, 4) a sufficiently long trap to achieve a constant velocity and to minimize the variation in power output resulting from torque or cadence fluctuations between individual pedal strokes, 5) that the riders held consistent body positions between different power outputs and experimental conditions, and 6) that the power meters used were reliable and valid. Of these factors, the only two that created an issue were wind and accelerations within the collection trap. Accordingly, trials were eliminated when the mean wind velocity exceeded 1.0 m·s⁻¹ or when there was a measured acceleration through the collection trap that was greater than 0.5 m·s⁻². Still, only 20% of the data needed to be excluded and all but two of the original subjects needed to be eliminated due to excessive winds.
Despite these potential sources of error, the lowest correlation coefficient obtained between tractive resistance and velocity squared for all of our subjects and experimental conditions using only 5 (women) or 7 (men) trial doublets in each regression was 0.9951 with a mean ± SD of 0.9959 ± 0.0028. These values were significantly higher than the range reported by Grappe et al. (1997) using the Look Max One rear hub power meter (r = 0.90 to 0.95; n = 12 trials x 4 conditions) and also higher than the values reported by Di Prampero et al. (1979) (r = 0.98, n = 33 trials) and Capelli et al. (1993) (r = 0.97; n = 40 trials and r = 0.96; n = 19 trials) during measurements of tractive resistance while towing at distinct velocities (4, 8, 10).

While our strong and linear correlations do not imply that our data is more accurate, they do suggest that for any given increase in velocity the protocol and power meters used were extraordinarily reliable in their ability to measure an appropriate increase in aerodynamic resistance.

Outside of re-assessing each subject’s aerodynamic profile with another technique, the most practical way of understanding the potential accuracy of our aerodynamic measures is to simply compare them with those reported previously for road cyclists. The aerodynamic character of cyclists, however, can differ dramatically depending upon the body position, clothing, wheels, and bicycle frame used (2-4, 10, 15). Thus, a direct comparison of our values with others is limited by the unique equipment, body position, and morphology of our subjects.

Notwithstanding, our mean values do compare favorably with those reported in the literature for similar body positions and equipment. Using cyclists on standard road bicycles, with spoked wheels, and in a dropped position, Pugh has reported a
mean $A_d$ value of 0.33 m$^2$ (n=4), while Davies and di Prampero have reported mean values of 0.28 m$^2$ (n=15) and 0.32 m$^2$ (n=2), respectively (6, 8, 21). While these values are similar to our mean ± SD $A_d$ value of 0.32 ± 0.05 m$^2$ for the dropped position, the techniques used in these previous studies were significantly more complex. For example, Pugh, after assessing the relationship between oxygen consumption and power on a laboratory ergometer, measured the metabolic cost of cycling along a level road at different velocities to determine $k$ and subsequently $A_d$. Likewise, Davies also determined the relationship between tractive resistance and velocity squared to calculate $k$ but regressed power after first measuring the metabolic cost associated with cycling against distinct wind velocities on a treadmill placed in a wind tunnel. While both protocols are limited by many of the same factors that affect our study, the additional sources of error introduced by the metabolic measuring equipment and the accuracy of these measures raises questions about the precision of these techniques. In contrast, di Prampero determined $A_d$ from $k$ in two subjects by directly measuring tractive resistance while towing cyclists behind a motorcycle at several velocities. The correlation between tractive resistance and velocity squared, however, were not as strong as those determined with our protocol and may have been adversely affected by turbulence generated by the motorcycle.

At present, some authors have suggested that the most reliable technique for assessing aerodynamic resistance is a coast down or deceleration test performed in a large and enclosed hallway. Although this technique may not be specific to actual cycling in the field, it is promoted as more specific than wind tunnel measures and is highly reproducible and sensitive to slight changes in body position (3, 7). Using this
technique in what could be considered a similar body position as our dropped position, De Groot et al., evaluated $A_d$ in 7 subjects riding standard road bicycles with their hands on the brake hoods in a position they characterized as “racing.” In this position a mean $\pm$ SD $A_d$ of $0.32 \pm 0.04$ m$^2$ was found with a range of 0.28 to 0.38 m$^2$ (7). Not only is this mean identical to our own ($0.32 \pm 0.05$ m$^2$), the variability and range were also comparable with a broader range for $A_d$ of 0.27 to 0.44 m$^2$ found in the present study. This range is equivalent to a 39% difference in $A_d$ between our least and most aerodynamic subject, while the range found by de Groot et al., was equal to 26%.

These ranges demonstrate that even in a single body position, there are large differences between individuals in their aerodynamic profile – differences that can have significant performance consequences. For example, at a speed of 40 km·hr$^{-1}$ the power required to overcome aerodynamic resistance would be equal to 214 watts for our most aerodynamic individual and 350 watts for our least aerodynamic individual at sea level ($\rho = 1.16$ kg·m$^{-3}$). Thus, it is important to realize that although our mean value for $A_d$ in the dropped position is similar to the mean values reported in the literature, it is unlikely that mean values adequately represent the performance requirements of a given individual.

From the hoods to the drop position, our subject’s decreased their drag area from a mean $\pm$ SD of $0.36 \pm 0.05$ to $0.32 \pm 0.05$ m$^2$, which represents an average decline of $10.8 \pm 3.5\%$. The minimum declined from hoods to drops was 5.7% while the maximum decline observed was 17.8%. Like our results, Grappe et al., also using a rear hub power meter, demonstrated an 8.3% decline in drag area from 0.299 to
0.276 m² in a single individual when moving from the hoods to the drops, while Candau et al., using a deceleration test, reported a 6.6% decline from 0.355 to 0.333 m² in a single individual when moving from a trunk angle of 40 to 35 degrees (3, 10). Similarly, Jeukendrup et al., using modeled data from wind tunnel measures, predicted a 14% decline in Ad from 0.358 m² to 0.307 m² when moving from an upright to crouched position (11). Thus, our data is not only within the range reported on an absolute scale, the relative change in Ad associated with a change in body position also matches previous reports. Practically speaking, the relative decline from the hoods to the drops results in a proportional decrease in the power required to overcome aerodynamic resistance. For our subjects, this results in an average decrease from 290 to 260 watts at 40 km·hr⁻¹ at sea level when moving from the hoods to the drops. This would translate to an average time saving of two minutes and six seconds in a 40 km flat time trial.

In addition to aerodynamic measures, the tractive resistance protocol also allows the elucidation of rolling resistance and consequently a coefficient for rolling resistance. Like, our values for Ad, our values found for Cr compared well on both an absolute and relative basis compared to those modeled and measured in the literature. For example, Grappe et al., (1999) using a deceleration technique, found that increments in tire pressure (P_t) from 150 to 1200 kPa elicited a hyperbolic Cr response, described by the equation (9):

\begin{equation}
(11) \quad C_r = 0.1071 \cdot P_t^{-0.477}
\end{equation}
When this equation is applied to the two tire pressures employed during this investigation, the predicted $C_r$ values are 0.0044 (828 kPa), and 0.0061 (414 kPa). The actual mean values measured were 0.0047 and 0.0066 at 828 kPa and 414 kPa, respectively. This difference would result in a loss of one minute and thirty two seconds on average in a 40 km flat time trial at an equivalent power output. On an absolute scale, our actual values are only 6% greater at 828 kPa and 8% greater at 414 kPa. On a relative scale the predicted difference between the two tire pressures was 38.6% while the actual measured difference was 32%. Although the absolute and relative values compare well, the small differences found between predicted and actual may be explained by the use of clincher tires in our study and the use of tubular tires by Grappe et al., since tubular tires are generally thought to have a lower rolling resistance (13). In addition, the deceleration technique used by Grappe et al., may simply give lower values for $C_r$ due to the smoother floors often associated with indoor hallways. As an example, Candau and de Groot also measured lower mean values of 0.0041 and 0.0038 for $C_r$ at tire pressure ranges of 600 to 1000 kPa during deceleration tests on a linoleum floor (3, 7). In contrast, di Prampero, during tractive resistance measures while towing cyclists found a mean value for $C_r$ of 0.0047 – a value equivalent to our own for 828 kPa (8).

In conclusion, the techniques described here when used with the Power Tap and SRM power meters are sufficiently precise to distinguish the affects of body position and tire inflation pressure on measures of aerodynamic and rolling characteristics, giving drag area and rolling coefficient values that compare well with values reported in the literature on both relative and absolute scales. Compared to
The remainder of the $R_{TOT}$ for both uphill and level cycling is due primarily to rolling resistance, which is dependent upon the mass of the bicycle and rider, the acceleration of gravity, and a dimensionless coefficient describing the quality of the tire and road interface ($C_r$) (30).

(7) $R_r = m_{TOT} \cdot g \cdot C_r$

Because the $C_r$ for a given tire pressure, road surface, and tire type is relatively homogeneous (30, 66), the primary determinant of rolling resistance is the total mass of the system. Though rolling resistance is a small component of the $R_{TOT}$ in uphill and level cycling, large differences in rolling resistance between individuals could affect performance. If tire pressure is held constant, however, the variability in rolling resistance between different tires and body masses is relatively small (± .5 N) (30, 66). Ultimately, rolling resistance is an important component of the total resistance, but may not play a large role in differentiating performance since it is relatively homogeneous between cyclists.

While mass is simple to measure, assessing variables like $R_r$, $k$, and $A_d$ present a greater challenge. Presently, $k$ and $A_d$ can be assessed through wind tunnel measures (39-41, 50, 61), while $R_r$, $k$, and $A_d$ can be measured through towing experiments (12, 23), deceleration tests (11, 20), and through estimates of field power via indirect calorimetry (18, 65). These techniques, however, are relatively complex, have a number of limitations, and are not commonly performed. Recently, we have demonstrated that measuring power and speed in the field with cycle mounted power meters, is a viable and accessible technique for assessing an individual’s aerodynamic drag and rolling resistance (44). Under carefully controlled settings (i.e., level road,
other techniques for assessing aerodynamic drag and rolling resistance, this technique is accessible, relatively easy to control, and the most specific technique for a given individual and their equipment for road cycling. Because of the important performance consequences associated with changes in aerodynamic and rolling resistance this protocol is an important technique for better profiling individual cyclists and in conjunction with physiological measures should help coaches, athletes and scientists to better predict road cycling performance.

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References


CHAPTER V: PHYSIOLOGIC AND PHYSICAL DETERMINANTS OF LEVEL AND UPHILL CYCLING PERFORMANCE.

Abstract

Purpose: To predict uphill and level cycling performance using physiological determinants of endurance performance (i.e., VO₂ peak, lactate threshold, & economy) and physical factors which contribute to resistance during cycling (i.e., aerodynamics, body weight, & rolling resistance). Methods: Within three days of a graded exercise stress test in the laboratory an uphill (9.1 km) and level (22.1) time trial were randomly performed a week apart in 19 well to highly trained male cyclists. The aerodynamic resistance per velocity squared (k) and rolling resistance (R_r) were calculated in each subject from the slope and intercept, respectively, of tractive resistance vs. velocity squared. Power output and velocity during all lab and field tests were measured using a rear hub power meter (Cycleops Power Tap, Madison, WI). Results (mean ± SD): VO₂ peak, lactate threshold (LT), and economy (econ) were 4.67 ± 0.40 l·min⁻¹ (362 ± 30 watts), 76 ± 4.5% of VO₂ peak (271 ± 29 watts), and 73.5 ± 3.1 watts·I O₂⁻¹, respectively. Body weight, k, and R_r were 70.0 ± 8.0 kg, 0.17 ± 0.03 N·V⁻², and 4.9 ± 1.3 N, respectively. Mean uphill time was 31:27 ± 3:18 (min:sec) at a power output of 324 ± 29 watts, while mean level time was 31:24 ± 2:15 at 303 ± 26 watts. The correlation between uphill and level power (r = 0.90, p < 0.01) was significantly greater (p < 0.001) than the correlation between uphill and level time (r = 0.57, p = 0.01). The ability to predict uphill performance time improved significantly (p < 0.05) when uphill power (r = -.42 vs. -0.94, p = 0.08 vs. <
0.001), VO_2 peak (r = -0.31 vs. -0.82, p = 0.19 vs. < 0.001), and power at LT (r = -0.46 vs. -0.82, p = .05 vs. < 0.001 were normalized to body weight. Likewise, the ability to predict level performance time improved significantly (P < 0.05) when level power (r = -0.59 vs. -0.92, p = 0.01 vs. < 0.001), power at VO_2 peak (r = -0.42 vs. 0.92, p = 0.08 vs. < 0.001), and power at LT (r = -0.45 vs. -0.85, p = 0.06 vs. < 0.001) were normalized to aerodynamic resistance represented as k. Economy and rolling resistance were not related to field time or power. It is notable that alone, k was better correlated to level time (r = 0.85, p < 0.001) than any single or group of physiological measures. Conclusions: Commonly recognized physiological determinants of endurance performance are not predictive of uphill or level performance in the field unless normalized to body weight or aerodynamics, respectively. Moreover, on the level aerodynamics alone are more predictive of performance than any physiological factor.

**Introduction**

Although competitive cycling can be tactically complex and involve substantial variation in effort, performance in cycling is ultimately determined by the velocity an athlete can sustain for a given distance or duration. This velocity is determined by a cyclist’s ability to produce or supply power and the forces that resist that cyclist’s forward motion (50, 55). Accordingly, performance in cycling would be optimized by maximizing a cyclist’s external power output while also minimizing the total resistance faced by that cyclist. Without a measure or estimate of these resistive demands, however, knowing a cyclist’s power output alone may not be enough to predict performance.
A cyclist’s ability to produce and sustain power is highly dependent upon physiological characteristics like their maximal aerobic capacity (VO₂ max), the lactate threshold (LT), and economy (Econ) (13-16). In the laboratory where resistive forces are controlled or minimized, these physiological factors have been successfully used to predict simulated time trial performance (6, 8, 13, 15, 16, 42, 45, 46, 52, 64). In the field, however, measures of a cyclist’s ability to supply power do not always predict performance even in the simplified arena of time trial racing (2, 36). For example, Balmer et al. (2000) demonstrated that while peak power output assessed during a graded exercise stress test does correlate highly (r = 0.99, p<0.001) with the average power assessed during a 16.1 km field time trial, neither the laboratory peak power output nor the average power during the time trial correlated well with performance time (r = 0.46, p > 0.05). These results demonstrate that the resistance faced by competitive cyclists is variable enough that power alone may not predict performance.

The total resistance ($R_{TOT}$) impeding the forward motion of a bicycle-rider system (system) is a function of aerodynamic resistance ($R_a$), rolling resistance ($R_r$), gravitational resistance ($R_g$), resistance due to changes in kinetic energy ($R_{\Delta ke}$), and frictional resistance in the drive train and structural components of the bicycle ($R_f$) (50).

$$R_{TOT} = R_a + R_r + R_g + R_{\Delta ke} + R_f$$

The contribution of each of these resistive elements to total resistance is greatly influenced by terrain and velocity. While cycling up a steep grade at low velocity (< 20 km·hr⁻¹), close to 90% of the $R_{TOT}$ is determined by gravitational
resistance, which is dependent upon the mass of the bicycle and rider \( m_{\text{TOT}} \) and the acceleration of gravity \( g \).

(2) \[ R_g = \sin \text{(Road Angle)} \cdot m_{\text{TOT}} \cdot g \]

Accordingly, for a given road angle, the gravitational resistance is directly proportional to the mass of the bicycle and rider. Thus, uphill cycling performance should be predicted by a cyclist's power to weight ratio or physiological attributes normalized to body weight. In fact, amongst professional cyclists the power to weight ratio at the lactate threshold and maximal aerobic capacity normalized to body weight are highly predictive of uphill cycling performance. They are not, however, predictive of level ground performance (48, 62).

While cycling on level terrain at constant and elevated velocities (>40 km·hr⁻¹), more than 90% of the \( R_{\text{TOT}} \) is determined by aerodynamic resistance \( R_a \), which is in turn, a function of the air density \( \rho \), projected frontal area of the bicycle and rider \( A_p \), a drag coefficient influenced by the shape of the bicycle and rider \( C_d \), and velocity squared \( V^2 \).

(3) \[ R_a = 0.5 \cdot \rho \cdot A_p \cdot C_d \cdot V^2 \]

Since velocity affects the actual aerodynamic resistance faced by a cyclist, it is easier to describe the aerodynamic character of a cyclist independent of velocity as the product of air density, projected frontal area, and the drag coefficient. Also known as \( k \), this value represents aerodynamic resistance per velocity squared. At a given velocity, differences in \( k \), either within or between individuals, result in proportional
differences in $R_x$. Accordingly power normalized to $k$ should predict performance on flat terrain.

(4) \[ k = 0.5 \rho \cdot A_p \cdot C_d \]

To compare individuals independent of the environment or if the environment is similar, power output can be normalized to the product of the projected frontal area and the drag coefficient, a term referred to as the drag area ($A_d$) (18, 31, 38, 39, 50, 65).

(5) \[ A_d = A_p \cdot C_d \]

Because measuring $k$ and $A_d$ can be complex, aerodynamic resistance is sometimes assumed from actual measures of $A_p$ or estimates of $A_p$ (18, 20, 23, 33, 35, 58-60). This assumes, however, that between individuals, aerodynamic resistance changes predictably with changes in $A_p$. Unfortunately, evidence exists to the contrary. For example, Kyle has shown that despite a 19% difference in the projected frontal area between two individuals, the aerodynamic resistance measured in a wind tunnel differed by only 1% due to an 18% difference in $C_d$ (41). Similarly, de Groot et al. using a deceleration test measured an individual whose aerodynamic drag was 20% greater than another individual despite having an $A_p$ that was 14% less (20). Though these are individual examples, it is likely that the coefficient of drag, which is influenced by the shape of the bicycle and rider, varies greatly between individuals and does not change proportionally with changes in projected frontal area. Thus, it appears that power normalized to $k$ or $A_d$, calculated for the bike and rider system, would best predict level performance.
The remainder of the $R_{TOT}$ for both uphill and level cycling is due primarily to rolling resistance, which is dependent upon the mass of the bicycle and rider, the acceleration of gravity, and a dimensionless coefficient describing the quality of the tire and road interface ($C_r$) (30).

\[(7) \quad R_r = m_{TOT} \cdot g \cdot C_r\]

Because the $C_r$ for a given tire pressure, road surface, and tire type is relatively homogeneous (30, 66), the primary determinant of rolling resistance is the total mass of the system. Though rolling resistance is a small component of the $R_{TOT}$ in uphill and level cycling, large differences in rolling resistance between individuals could affect performance. If tire pressure is held constant, however, the variability in rolling resistance between different tires and body masses is relatively small ($\pm .5$ N) (30, 66). Ultimately, rolling resistance is an important component of the total resistance, but may not play a large role in differentiating performance since it is relatively homogeneous between cyclists.

While mass is simple to measure, assessing variables like $R_r$, $k$, and $A_d$ present a greater challenge. Presently, $k$ and $A_d$ can be assessed through wind tunnel measures (39-41, 50, 61), while $R_r$, $k$, and $A_d$ can be measured through towing experiments (12, 23), deceleration tests (11, 20), and through estimates of field power via indirect calorimetry (18, 65). These techniques, however, are relatively complex, have a number of limitations, and are not commonly performed. Recently, we have demonstrated that measuring power and speed in the field with cycle mounted power meters, is a viable and accessible technique for assessing an individual’s aerodynamic drag and rolling resistance (44). Under carefully controlled settings (i.e., level road,
no external wind, & steady velocity), k and R, calculated as the slope and intercept, respectively, of tractive resistance (power ÷ speed) versus velocity squared, can be measured independently of one another with absolute and relative values that are comparable with those found using other methods (44). Thus, the possibility now exists to perform highly specific and accurate measures of aerodynamic drag and rolling resistance using a technique that is relatively simple and accessible.

Not only could this technique in combination with standard physiological profiling improve our ability to predict field performance, it has been argued that physical factors resisting forward motion play a larger role in performance outcome than physiological variables (38). Using a mathematical model developed by Martin et al., Jeunkendrup estimated that the time saving for an elite cyclist climbing up a 6% grade using a 10 kg versus 7 kg bicycle would be 1 minute and 15 seconds. Up a 12% grade, the time saving would be 2 minutes and 48 seconds. On the level by optimizing body position and bicycle aerodynamics an elite cyclist could save as much as 6 minutes compared to an upright position with hands on the hoods (38, 50). Finally, a mathematical model developed by Grappe et al., shows that a decrease in tire pressure from 120 to 60 psi (828 to 414 kPa) would result in a loss of 1.5 minutes in a 40 km time trial (30). All things being equal, at a speed of 40 km·hr⁻¹ a one-minute improvement in time would theoretically require an additional 10 to 15 watts of extra power or a 3 to 5% decrease in drag area. Assuming an average economy of 75 W·L O₂⁻¹ this would increase the oxygen consumption of a 70 kg cyclist by 0.15 to 0.20 l·min⁻¹ (13, 14), which would be equivalent to a 4% increase in VO₂ max for each minute improvement in time. Essentially, a 1% increase in drag area would
increase the required oxygen cost of forward motion by approximately 1%. When considering that in a single body position the standard deviation in drag area between individuals has been measured at 12.5% with ranges exceeding 25%, the potential performance impact for athletes who are physiologically similar can be tremendous (18, 20).

Although it is clear that performance is a function of a cyclist’s physiological capacity to produce power and physical factors resisting forward motion, the assessment of aerodynamic drag and rolling resistance in conjunction with physiological measures of performance is uncommon if not absent in the current literature. This may be due to the difficulty of assessing aerodynamic drag and rolling resistance in a large number of subjects and the simple yet potentially inaccurate alternative of estimating these values from measures of projected frontal area. With our current ability, however, to measure these variables through field measures of power and velocity the possibility now exists to assess cycling performance from both a physiological and physical perspective.

Purpose:

Accordingly, the purpose of this study was to quantify physical factors that contribute to resistance during cycling (i.e., aerodynamics, rolling resistance, and body weight) in conjunction with physiological determinants of endurance performance (i.e., VO₂ max, lactate threshold, and economy) in well to highly trained male cyclists. Our intent was to examine the relationship between these physiological and physical measures with actual field measures of performance time and power output during an uphill and level time trial.
Hypotheses:

1) A cyclist’s physiological capacity or average power output in the field will not predict uphill performance time unless normalized to body mass or the system mass (bicycle + rider).

2) A cyclist’s physiological capacity or average power output will not predict level performance time unless normalized to some representation of aerodynamic resistance. Specifically, aerodynamic resistance per velocity squared (k) or drag area ($A_d$), but not the projected frontal area ($A_p$) or the estimated projected frontal area ($eA_p$).

3) Although, there will be a strong relationship between the average power output during the uphill versus level time trial, there will not be a strong relationship between performance time during the uphill versus level time trial.

4) Physiological capacity, measured in the laboratory as maximal or peak aerobic capacity ($VO_2$ peak), lactate threshold (LT), and economy (econ) will correlate strongly to average power output during an uphill and level time trial in the field.

5) The combination of $VO_2$ peak (l·min$^{-1}$), LT (% of $VO_2$ peak), and econ (watts·l $O_2$·$^{-1}$ at LT) will best predict average power output in both time trials, while LT will be the best single predictor of average power output in both time trials.

6) Rolling resistance will play a negligible role in performance outcome in both time trials.
Methods

Subjects:

Nineteen well to highly trained male cyclists volunteered for this study. All subjects were licensed, competitive cyclists (United States Cycling Federation Category Pro/1/2 Road or Pro/Expert MTB) living, training, and racing in the Boulder/Denver area for a minimum of two months. The Human Research Committee at the University of Colorado at Boulder approved the protocol used for this study.

Project Overview:

Subjects performed an uphill and level time trial on open roads in random order exactly one week one week apart. Laboratory testing was conducted within three days of one of the time trials. Within three weeks of the last time trial, aerodynamic drag and rolling resistance were measured on the bicycle(s) and in the body position used during each time trial by measuring the power versus speed relationship at four distinct power outputs on a level road. Projected area was also measured at this time using digital planimetry from digital photographs. Subjects reported their training load and diet during the two days leading up to each test and were asked to maintain a consistent diet and training load during these two days. All tests were performed during the height of the competitive cycling season in Colorado (Summer to early Fall).

Power Measuring Devices and Calibration:

All subjects utilized a rear hub power meter (Cycleops Power Tap) that was set to record external power output, ground velocity, cadence, heart rate, and time
with power output measured at a frequency of 61 Hz with data averaged and recorded in increments of 1.26 seconds for all variables. Nineteen distinct power meters were used throughout the study, one for each subject. Each subject used the same power meter for the uphill and level time trial, laboratory testing, and aerodynamic/rolling resistance measures.

Although this power meter has been shown to be accurate and reliable in previous work by our laboratory and others, each power meter used in this particular study was tested before use against an external dynamometer (25, 28). No difference was found in the slope of the power measured with the power meters versus the dynamometer. A small but significant difference, however, was found between the intercept – a difference attributable to mechanical losses between the bottom bracket and rear hub. Finally, no difference was found in the slope or intercept for measured power between the power meters used.

Prior to commencing trials all units used during testing were calibrated against a zero torque reference while pedals were stationary and unloaded as directed by the manufacturer.

For the calculation of ground velocity, wheel circumference was initially measured directly with riders atop inflated tires but later standardized to a value of 2096 mm for the corresponding combination of rim diameter (622 mm) and tire height (~23 mm) found with the 700 C rims and 23 mm “clincher” tires used by all subjects. This standardization stemmed from the finding that the maximum discrepancy between the circumference value of 2096 mm and that measured was
only 10 mm (~0.5%) – a range that was within the sensitivity of our ability to measure velocity.

Laboratory Measures and Protocol:

Laboratory performance variables (peak oxygen consumption, economy, lactate threshold, heart rate, perceived exertion, and power output) were measured during a graded exercise stress test conducted within three days of a subject’s time trial. Each test was performed on the subject’s personal road bicycle attached to an electronically braked trainer (CompuTrainer®) with power measured using the rear hub power meter loaned to the subject at the beginning of the study. The protocol began at a power output between 100 to 150 watts, increasing by approximately 30 watts every 4 minutes until volitional fatigue. All tests were conducted at an altitude of 1,625 meters (5,330 feet) with an average barometric pressure, temperature, and humidity of 630.5 ± 3.4 mmHg, 22.9 ± 1.4 °C, and 37.1 ± 6.9%, respectively. In addition, a fan set at high was used to cool subjects throughout each test.

Oxygen consumption was measured every 15 seconds through computer assisted indirect calorimetry using Parvomedics software and hardware to integrate input from a Validyne pressure tranducer linked to a Hans Rudolph pneumotach measuring inspired ventilation and a Perkin Elmer mass spectrometer sampling from a 4-liter mixing chamber. Before each test, gas fractions were calibrated against a primary standard within the physiologic range (≈ 15% O₂ & 5% CO₂), while the pneumotach was calibrated using a 3-liter syringe at 5 distinct flow rates (≈ 50 l·min⁻¹ to 300 l·min⁻¹ ATPS). In addition, a 2-minute mechanical check was performed before and after each test using the primary standard and a flow rate of 60 l·min⁻¹ ATPS.
From pre to post mechanical checks ventilation remained within 1% and gas fractions within 0.3% of original calibration values.

Peak oxygen consumption was defined as the highest rate of oxygen consumption for a sampling interval of one minute during the graded exercise stress test. Subjects were encouraged to give a maximal effort and in all cases exceeded a respiratory exchange ratio of 1.15 and a blood lactate of 7 mM at volitional exhaustion. For the measure of economy (econ) only the oxygen consumed over the last two minutes of each 4-minute stage was used to ensure steady state measures. Economy was measured as the ratio between power output and oxygen consumption (Watts/l O₂) at the lactate threshold from a regression of the oxygen consumption versus power relationship. In all subjects, the relationship between oxygen consumption and power output was linear (r > 0.99) through the penultimate stage.

Blood lactate was measured at rest and over the last minute of each 4-minute stage. For each sample, approximately 50 μl of blood was drawn via finger pricks into a 75 μl capillary syringe. Twenty-five μl was then mixed with a “cocktail” containing 50 μl of a buffer, lysing (Triton XL-100), and anti-glycolytic (sodium fluoride) solution. Lactate was finally sampled using a YSI 2300 lactate analyzer. Before each test, the lactate analyzer was calibrated against a known standard, and re-calibrated every 15 minutes.

The lactate threshold was defined as a point 1 mM above a baseline that included resting lactate (Coyle, 1984). The average value for these points determined from eight independent observers was used in data analysis. No significant difference was found between observers.
Heart Rate was measured using radio telemetry (Polar®) each minute while perceived exertion was measured using the Borg 6-20 scale 2 minutes into each stage.

Within two days of the laboratory test, body composition was assessed using dual energy x-ray absorptiometry. Extended analysis was performed on each scan by three independent observers. No significant difference was found between observers. The mean between observers was used in data analysis.

*Uphill and Level Time Trial:*

The uphill time trial was conducted on Flagstaff road in Boulder, Colorado. The total distance of the climb to the summit was 9.09 km (5.64 miles) with a starting elevation of 5,488 feet and a final elevation of 7,738 feet. With a net gain of 2,250 feet, the average grade was 6.87%. The section of road selected was continuous with no stop signs or traffic lights to impede the subjects. All uphill time trials were conducted on standard road racing bicycles with spoked clincher wheels.

The level time trial was conducted over two laps of a four-corner loop in Hygiene, Colorado. The total distance of the level time trial was 22.1 km (13.7 miles). Over the course of each lap subjects gained and lost 259 feet of elevation for a net elevation gain of 0 feet. The layout of the course allowed the subjects to ride continuously with no stop signs or traffic lights impeding their effort. Subjects were allowed to utilize time trial bicycles equipped with time trial bars and an aerodynamic front wheel. Six subjects rode their standard road bike with no additional aerodynamic equipment. Four subjects rode their standard road bike equipped with aerodynamic handlebars. Finally, nine subjects utilized a time trial bicycle equipped...
with aerodynamic handlebars with an aerodynamic deep dish or three-spoked front wheel.

Within two weeks of the uphill and level time trial subjects were asked to pre-ride the courses to re-familiarize them with the routes. All subjects had previous experience training on the selected courses. Just prior to each time trial, subjects were asked to warm-up in the same way they would for a real competitive event and given as much time as they needed to adequately warm-up. At this time, tires were inflated to 120 psi with the riders off the bicycle. Immediately before each time trial the subject’s body weight and bicycle weight were measured using an electronic scale previously calibrated against a laboratory balance scale (Detecto Scales, Webb City, MO). At the start line, the on board computers were cleared and the power meters calibrated against a zero load. During the time trial subjects were blinded from viewing their power output but allowed to view speed, time, distance, cadence, and heart rate. In addition to the time measured by the on board computer, performance time was also measured using an external stopwatch.

All time trials were held between 9 am and 11 am. Air density was calculated from measures of ambient temperature, station pressure, and relative humidity collected with a Vantage Pro model weather instrument (Digital Instruments, Enterprise, OR). Though an attempt was made to schedule as many subjects as possible on the same day to control for wind, environmental conditions, and the competitive atmosphere a total of nine separate level and uphill time trials were performed with six subjects performing the time trials alone and the others on one of three occasions. During these separate occasions the time trials were allowed to
proceed as long as the wind did not exceed a 3 or a “gentle breeze” on the Beaufort
Wind Scale. This is equivalent to a wind speed less than 20 km·hr⁻¹ characterized by
surroundings in which smoke rises vertically (0) to a wind velocity were smoke
moves horizontally and small branches begin to sway (3).

Data Reduction and Analysis:

Immediately after each time trial, data collected from the power meter was
downloaded from the onboard computer to an Apple G4 computer. Downloaded data
included time, power output, speed, cadence, and heart rate in 1.26-second intervals.
Using Power Coach™ (Kochli Sport, Sonvilier, Switzerland) software operated by
Apple G4 computers, the performance time measured using the external stopwatch
was located on the data download and isolated. The distance from this isolated data
was then checked to ensure that it matched the actual distance of the course. The data
isolated in this manner did not vary by more than 50 meters (7.26 ± 4.26 sec) from
the actual distance of the course. Because heart rate, power and speed data are
transmitted to the onboard computer using radio telemetry, the data was next checked
for any potential recording problems. When a problem in data transmission does
occur, the clock on the onboard computer continues to run, but speed and power are
marked as zero. Because, none of the subjects stopped during any time trial, if an
interval of data was found to contain a zero speed or heart rate, that line of data was
interpolated between the adjacent data points. On average, approximately four
seconds of data was lost in any given time trial, with no more than 2 data points ever
occurring simultaneously, with a range of 0 seconds to 24 seconds lost. Finally, the
statistics of interest were calculated using specific code written for Matlab® (Mathworks Inc., Berkeley, CA).

*Aerodynamic Profiling:*

Aerodynamic and rolling resistance were calculated by measuring the power versus velocity relationship while subjects cycled over a level section of road adjacent to the Boulder Airfield in Boulder, Colorado. The section of road or “collection trap” (CT) stretched 200 m and was flanked at either end by “acceleration distances” of 400 to 500 m, was comprised of smooth black asphalt, and was flat with a slight roll over the course that did not vary by more than 0.135° or 0.03%. Subjects were instructed to ride at a constant velocity in both directions (east and west) along the CT at four distinct power outputs (≈ 100, 200, 300, and 400 watts). At the end of a given pass in one direction, subjects ceased pedaling for 20 to 50 m to mark the end of the CT in the data download.

All tires were inflated to 828 kPa (120 psi) with the riders off the bicycle. Subjects were tested using the same body position, clothing, and equipment from each time trial. Air density was calculated from measures of ambient temperature, station pressure, and relative humidity. All trials were completed in the early morning between 6 to 8 am when wind conditions are generally the calmest in Boulder, Colorado. Trials were conducted as long as the wind remained at a 0 to 1 or “calm” to “light air” on the Beaufort Wind Scale. This is equivalent to a wind speed less than 5 km·hr⁻¹ characterized by surroundings in which smoke rises vertically or moves slightly with a breeze. If subjects or researchers could feel the wind on their face
while standing still or if the windsocks adjacent to the airport rose, trials were rescheduled or repeated.

Power output \( (P_{\text{ext}}) \) and velocity \( (V) \) were analyzed using Power Coach™ (Kochli Sport, Sonvilier, Switzerland) software operated by Apple G4 computers. This software presents data \((V, P_{\text{ext}}, \text{Time}, \text{Distance})\) as discrete points representing averages of the recording interval (1.26 seconds). In analysing data from each trial, all points contributing to the 200 m distance preceding the point at which subjects ceased pedalling \((P_{\text{ext}} = 0)\), were averaged for both \(V\) and \(P_{\text{ext}}\). Additionally, the final data point (directly preceding \(P_{\text{ext}} = 0)\) was always excluded so that trials in which subjects ceased pedalling at a time before the finish of the final 1.26-second average were not contaminated by an underestimate of the true \(P_{\text{ext}}\) value.

The \(P_{\text{ext}}\) and \(V\) values achieved through this process were then averaged for the east and west directions to give a mean external power output and mean system velocity for each prescribed power output. These mean values for \(P_{\text{ext}}\) and \(V\) from the east and west trials comprised the data points used to determine tractive resistance.

Ttractive resistance was calculated as power (watts) divided by velocity \((\text{m} \cdot \text{s}^{-1})\). A best-fit regression was then used to assess the relationship between tractive resistance \((y)\) and velocity squared \((x)\). In all cases, this relationship was linear yielding a slope equal to aerodynamic resistance per velocity squared \((k)\) and an intercept equal to rolling resistance. Drag area was calculated by dividing the aerodynamic drag by one-half air density. Finally, a coefficient for rolling resistance was calculated by dividing rolling resistance by the mass of the subject and bicycle system and the acceleration of gravity.
Projected Frontal Area:

Digital photographs (Nikon Cool Pix 4300, Melville, NY) of the subjects were taken while subjects rode their road and/or time trial bicycle on a stationary trainer. The camera was set at the level of the handlebars 3 meters away from the edge of the front wheel. The shortest focal length available on the camera was used to fill the cyclist within the frame. The camera was set in its “best shot selection” mode allowing the most focused of ten automatically shot photos to be selected. Photos were taken of each cyclist in each of the body positions used during the uphill and level time trial and in three different foot positions -- pedaling, with feet at the 3 and 9 o’clock position, and with feet at the 6 and 12 o’clock position. For each subject a reference board with 10 cm square tracings was also photographed. The reference board was set perpendicular to and directly over the center of the top tube of the bicycle. All photos were downloaded to an Apple G4 computer for analysis.

Photographs were analyzed using NIH Image 1.62 software. This software, after calibration against a known distance or area, automatically calculates the area of a given tracing. Projected area was calculated from tracings of the subject’s body and helmet only with the bicycle excluded. Three independent observers performed three tracings for each subject in each body and foot position. No difference was found within or between observers for measures of projected area for any subject. In addition, no difference was found within or between observers for the three distinct foot positions. The mean from all observers and all foot positions was used for data analysis and reported measures of projected area.
In addition to actual measures of projected frontal area, an estimate of projected frontal area was made by using an adjustment of Dubois equation for total frontal surface area from height and weight. Estimated projected frontal area was estimated from mass (kg) and height (cm) by taking 18.5% of the frontal surface area formula by Dubois \((0.007184 \times \text{Mass}^{0.425} \times \text{Height}^{0.725})\) (24).

**Statistical Analyses:**

Bivariate correlations were performed to assess the relationship between physical, physiological, and normalized variables to time and power measured during the uphill and level time trial. In addition, stepwise multiple regressions were performed to locate the best single or combination of variables predictive of uphill and level time and power. Differences between correlation coefficients were then located using the Hotelling test. Finally, a two-tailed paired t-test was used to compare results from the uphill and level time trial. Significance for all calculations was set at a p-value less than 0.05. Descriptive data were represented as the mean, standard deviation, minimum, and maximum.

**Results**

Descriptive characteristics of our nineteen subjects are presented in Table 4-1, while results from the laboratory testing are presented in Table 4-2. All data is given as the mean ± standard deviation (SD) with minimum (min) and maximum (max) values included. The average age of our subjects was 27.6 ± 4.6 years, with a mean height and weight of 174.0 ± 6.0 cm and 70 ± 8.0 kg, respectively. The mean \(\text{VO}_2\) peak was
Table 4-1. Mean (±SD), minimum, and maximum descriptive information for all 19 subjects.
<table>
<thead>
<tr>
<th>Age (years)</th>
<th>27.6 ± 4.6</th>
<th>20</th>
<th>36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>174.0 ± 6.0</td>
<td>164</td>
<td>184</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>70.0 ± 8.0</td>
<td>59.5</td>
<td>87.3</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>10.4 ± 2.64</td>
<td>6.0</td>
<td>16.5</td>
</tr>
<tr>
<td>Bone Density (g·cm²)</td>
<td>1.22 ± 0.11</td>
<td>1.03</td>
<td>1.41</td>
</tr>
<tr>
<td>Years Racing</td>
<td>8 ± 5</td>
<td>3</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 4-2. Mean ± SD, minimum, and maximum values for the primary physiological performance measures assessed during the laboratory graded exercise stress test in all 19 subjects.
<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>VO₂ peak (l/min⁻¹)</td>
<td>4.67 ± 0.40</td>
<td>3.91</td>
<td>5.47</td>
</tr>
<tr>
<td>VO₂ peak (ml kg⁻¹ min⁻¹)</td>
<td>67.6 ± 6.4</td>
<td>54.2</td>
<td>76.5</td>
</tr>
<tr>
<td>Power at VO₂ peak (Watts)</td>
<td>3.62 ± 3.6</td>
<td>3.08</td>
<td>4.10</td>
</tr>
<tr>
<td>Power to Mass at VO₂ peak (Watts)</td>
<td>5.15 ± 0.51</td>
<td>4.21</td>
<td>5.95</td>
</tr>
<tr>
<td>LT 1 mM as % of VO₂ peak</td>
<td>76 ± 4.5</td>
<td>65</td>
<td>82</td>
</tr>
<tr>
<td>Power to Mass at LT 1 mM (Watts)</td>
<td>2.71 ± 2.9</td>
<td>2.30</td>
<td>3.31</td>
</tr>
<tr>
<td>Power to Mass at LT 1 mM (Watts)</td>
<td>3.87 ± 0.48</td>
<td>3.03</td>
<td>4.53</td>
</tr>
<tr>
<td>Economy (W·l/O₂)</td>
<td>73.8 ± 3.1</td>
<td>69.1</td>
<td>78.9</td>
</tr>
<tr>
<td>Max HR (bpm)</td>
<td>183 ± 8</td>
<td>168</td>
<td>197</td>
</tr>
</tbody>
</table>
4.67 ± 0.40 l O₂·min⁻¹ (67.6 ± 6.4 ml·kg⁻¹·min⁻¹) with a lactate threshold of 76 ± 4.5% of VO₂ peak, and economy of 73.5 ± 3.1 W·l O₂⁻¹.

The primary components of aerodynamic resistance (air density, \( k \), \( A_d \), \( A_p \)), rolling resistance (\( R_r \)), the coefficient of rolling resistance (\( C_r \)), and mass are presented in Table 4-3 for the bicycle rider system (bicycle, equipment, and body position) used in the uphill and level time trial. Uphill, the mean \( k \) and \( A_d \) was 0.203 ± 0.03 N·m⁻²·s⁻² and 0.409 ± 0.063 m², respectively, while on the level the mean \( k \) and \( A_d \) was 0.170 ± 0.028 N·m⁻²·s⁻² and 0.341 ± 0.059 m², respectively. The mean \( A_p \) (rider only) uphill was 0.416 ± 0.035 m² and 0.339 ± 0.059 m² for the level. Because the \( A_p \) was calculated with the rider only while the \( A_d \) was calculated for the entire bicycle and rider system, it would be technically incorrect to calculate a \( C_d \) for the bicycle and rider system or rider alone. Still, dividing \( A_d \) by the \( A_p \) would give a virtual \( C_d \) of 0.98 ± 0.13 uphill and 1.02 ± 0.11 on the level. The mean \( R_r \) and \( C_r \) uphill was 4.48 ± 1.18 N and 0.006 ± 0.001, respectively, and 4.88 ± 1.27 N and 0.006 ± 0.002, respectively on the level. Significant difference was found for \( k \), \( A_d \), and \( A_p \) (\( p < 0.001 \)), but not for a virtual \( C_d \) (\( p = 0.094 \)) between the uphill versus level bicycle/position. For the level time trial position, a strong and significant correlation was found between \( k \) and \( A_d \) (\( r = 0.993 \), \( p < 0.001 \)). No relationship, however, was found between \( A_p \) and the virtual \( C_d \) (\( r = -0.170 \), \( p = 0.486 \)). No significant difference was found between the \( A_p \) and the estimated \( A_p \) in the level time trial position (\( p = 0.616 \)), though a significantly greater \( A_p \) was measured for the uphill position (\( p < 0.001 \)). No significant difference was found between rolling resistance and the coefficient of rolling resistance between the uphill and level time trial. No correlation
Table 4-3. Mean ± SD, minimum, and maximum values for the primary determinants of aerodynamic and rolling resistance measured on the bicycle and body position used during the uphill and level time trial.
<table>
<thead>
<tr>
<th>Time &amp; Distance</th>
<th>Uphill Time Trial Bicycle</th>
<th>Level Time Trial Bicycle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Min</td>
</tr>
<tr>
<td>Air Density (kg·m⁻³)</td>
<td>1.00 ± 0.02</td>
<td>0.98</td>
</tr>
<tr>
<td>k constant (N·m⁻²·s⁻²)</td>
<td>0.203 ± 0.03†</td>
<td>0.150</td>
</tr>
<tr>
<td>Aₚ (m²)</td>
<td>0.409 ± 0.063†</td>
<td>0.300</td>
</tr>
<tr>
<td>Virtual C₄</td>
<td>0.981 ± 0.128†</td>
<td>0.786</td>
</tr>
<tr>
<td>Aₚ (m²)</td>
<td>0.416 ± 0.035‡*</td>
<td>0.370</td>
</tr>
<tr>
<td>Estimated Aₚ (m²)</td>
<td>0.343 ± 0.022</td>
<td>0.310</td>
</tr>
<tr>
<td>Rₐ (N)</td>
<td>4.48 ± 1.18</td>
<td>2.95</td>
</tr>
<tr>
<td>Cᵥ (dimensionless)</td>
<td>.006 ± 0.001</td>
<td>.004</td>
</tr>
<tr>
<td>Total Mass (kg)</td>
<td>79.73 ± 8.44</td>
<td>68.86</td>
</tr>
</tbody>
</table>

† Significantly different than the level time trial bicycle and body position (p < 0.05).
* Significantly different from the estimated Aₚ (p < 0.05).
was found between total mass and k uphill ($r = 0.318$, $p = 0.185$) or on the level ($r = 0.302$, $p = 0.208$).

The results of the uphill and level time trial are presented in Table 4-4. The mean ± SD time of the uphill and level time trial was 31:27 ± 03:18 (min:sec) and 31:24 ± 02:15, respectively. No significant difference was found in the total time between the uphill and level time trial ($p = 0.911$) though there was a significant difference in velocity ($17.52 ± 1.44$ vs. $42.4 ± 2.37$ km·hr$^{-1}$, $p < 0.001$).

With respect to environmental conditions, a significant difference was found in temperature (22.2 vs. 26.2 °C), humidity (40.2 vs. 30.7%), and air density (0.98 vs. 0.97) ($p < 0.01$) between uphill and level time trials, though no difference was found in barometric pressure at the start line (628.1 vs. 629.2 mmHg) ($p = 0.281$).

Average power output was significantly greater during the uphill ($324 ± 29$ W) compared to the level ($303 ± 26$) time trial ($p < 0.001$). This difference was true for every individual, with a minimum difference of 4 watts and a maximum difference of 56 watts. The absolute wattage difference between the uphill and level time trial was significantly correlated to time spent below LT ($r = 0.83$, $p < 0.001$), but was not related to time spent at zero watts ($r = -0.30$, $p > 0.05$). Power output was more variable in the level compared to the uphill time trial as reflected by a significantly greater standard deviation in power during the level ($80 ±14$ W) compared to the uphill ($55 ± 10$ W) time trial ($p < 0.001$). Subjects held an average of 89.7% and 84.1% of power at VO$_2$ peak on the uphill and level, respectively. This was equivalent to 119.7% and 112.4% of the power at LT 1 mM for the uphill and level time trial, respectively.
Table 4-4. Mean ± SD as well as minimum and maximum values for the performance and environmental variables measured during the uphill and level time trial.
### Uphill Time Trial (9.09 km)

<table>
<thead>
<tr>
<th>Time &amp; Distance</th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avs ± SD</td>
<td>Min</td>
</tr>
<tr>
<td>Total Time (min:sec)</td>
<td>31:27 ± 3:18</td>
<td>27:02</td>
</tr>
<tr>
<td>Speed (km-hr⁻¹)</td>
<td>17.52 ± 1.44</td>
<td>13.87</td>
</tr>
</tbody>
</table>

### Environment

<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp (°C)</td>
<td>22.2 ± 2.0 † 18.0 25.0</td>
<td>26.2 ± 4.5 20.0 35.0</td>
</tr>
<tr>
<td>Humidity (%)</td>
<td>40.2 ± 8.2 † 26 59</td>
<td>30.7 ± 9.5 14 50</td>
</tr>
<tr>
<td>Pb (mmHg)</td>
<td>628.1 ± 1.6 623.3 631.2</td>
<td>629.2 ± 3.7 626.4 638.3</td>
</tr>
<tr>
<td>Air Density (kg-m⁻³)</td>
<td>0.98 ± 0.01 † 0.97 1.00</td>
<td>0.97 ± 0.02 0.95 1.00</td>
</tr>
</tbody>
</table>

### Power & Work

<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avs Power (W)</td>
<td>324 ± 29 † 279 380</td>
<td>303 ± 26 259 354</td>
</tr>
<tr>
<td>SD Power (W)</td>
<td>55 ± 10 † 37 74</td>
<td>80 ± 14 61 113</td>
</tr>
<tr>
<td>Avs Power (% of LT)</td>
<td>119.7 ± 7.0 † 110.3 135.1</td>
<td>112.4 ± 9.2 96.1 133.0</td>
</tr>
<tr>
<td>Avs. Power (% of VO₂ peak)</td>
<td>89.7 ± 5.4 † 75.0 96.4</td>
<td>84.1 ± 5.9 69.6 92.5</td>
</tr>
<tr>
<td>Avs. Power G, (W)</td>
<td>283 ± 27 249 338</td>
<td>- - -</td>
</tr>
<tr>
<td>Avs Power Rₘ, (W)</td>
<td>24 ± 5 † 13 32</td>
<td>272 ± 23 211 297</td>
</tr>
<tr>
<td>Avs. Power Rₚ, (W)</td>
<td>17 ± 2 † 18 24</td>
<td>31 ± 12 9.8 51</td>
</tr>
<tr>
<td>Avs Power (W·kg⁻¹)</td>
<td>4.61 ± 0.45 † 3.52 5.21</td>
<td>4.32 ± 0.44 3.27 4.98</td>
</tr>
<tr>
<td>Work (Kjoule)</td>
<td>609 ± 61 † 526 721</td>
<td>569 ± 42 513 641</td>
</tr>
<tr>
<td>EE (Kcal from Power)</td>
<td>706 ± 88 † * 590 869</td>
<td>660 ± 70 * 576 782</td>
</tr>
<tr>
<td>EE (Kcal from HR)</td>
<td>738 ± 83 619 859</td>
<td>723 ± 68 607 830</td>
</tr>
</tbody>
</table>

### Cadence & Torque

<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avs. Cadence (rpm)</td>
<td>73 ± 4 † 65 80</td>
<td>91 ± 6 81 102</td>
</tr>
<tr>
<td>Avs. Torque (N·m)</td>
<td>43.7 ± 5.1 † 38 55</td>
<td>32.4 ± 3.5 25 39</td>
</tr>
</tbody>
</table>

### Heart Rate

<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avs. HR (bpm)</td>
<td>175 ± 8 † 159 185</td>
<td>173 ± 6 161 183</td>
</tr>
<tr>
<td>SD HR (bpm)</td>
<td>8 ± 2 4 11</td>
<td>8 ± 2 4 11</td>
</tr>
<tr>
<td>Avs. HR (% of LT HR)</td>
<td>113.0 ± 3.9 104.4 117.6</td>
<td>111.9 ± 3.8 101.5 117.6</td>
</tr>
<tr>
<td>Avs. HR (% of Max HRₚ)</td>
<td>94.8 ± 1.2 92.1 96.7</td>
<td>95.5 ± 1.1 93.3 96.8</td>
</tr>
<tr>
<td>Max HR (bpm)</td>
<td>184 ± 8 † ¥ 167 198</td>
<td>180 ± 6.3 167 192</td>
</tr>
</tbody>
</table>

### Perceived Exertion

<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPE (Borg 6-20)</td>
<td>18.3 ± 1.1 † 16 20</td>
<td>17.4 ± 1.3 14 20</td>
</tr>
</tbody>
</table>

† Significantly different from the level time trial (p < 0.05).
* Significantly different from the EE calculated from heart rate (p < 0.05).
¥ Significantly different from laboratory maximal heart rate (p < 0.05).
Assuming that all of the resistance faced by the cyclists during the uphill time trial was due to gravitational, aerodynamic, and rolling resistance, and that all of the resistance faced by the cyclists during the level time trial was due to aerodynamic and rolling resistance, estimates of power for each component are given. For the uphill, gravitational power was calculated from each subject’s total mass (body and bicycle) and rate of ascent, aerodynamic power was calculated from the k measured for each subject’s uphill position, while rolling resistance was assumed to be the remainder of the power. For the level, aerodynamic power was calculated from the k measured for each subject’s level position while rolling resistance was assumed to be the remainder of the power. This method produced significantly lower values for C, for both the uphill (0.0046 ± 0.0013) and level (0.0034 ± 0.0023) time trial compared to those measured during the aerodynamic trials. Because of the greater velocity on the level, both aerodynamic power and rolling power are significantly greater during level compared to uphill cycling (p < 0.001). In the uphill time trial, gravitational, aerodynamic, and rolling resistance accounted for 87.35%, 7.41%, and 5.24% of the total power at 283 ± 27, 24 ± 5, and 17 ± 2 watts, respectively. In the level time trial, aerodynamic and rolling resistance accounted for 89.77% and 10.23% of the total power at 272 ± 23 and 31 ± 12 watts, respectively.

The total mechanical work (Kjoule) was significantly greater in the uphill (609 ± 61 Kj) than in the level (569 ± 42 Kj) time trial (p < 0.001). Likewise, energy expenditure in Kcals (EE), calculated from the laboratory oxygen consumption to power relationship was significantly greater in the uphill (706 ± 88 Kcals) than in the level (660 ± 70 Kcals) time trial (p < 0.001). The EE calculated from the laboratory
oxygen consumption to heart rate relationship, however, was the same for the uphill (738 ± 83 Kcals) and level (723 ± 68 Kcals) time trial (p = 0.378). Energy expenditure calculated from heart rate was greater in both the uphill (p = 0.006) and level (p < 0.001) time trial when compared to EE calculated from power output by an average of 32 Kcals uphill and 63 Kcals on the level.

Cadence (p < 0.001) and torque (p < 0.001) were significantly lower uphill (73 ± 4 rpm & 43.7 ± 5.1 N) compared to the level (91 ± 6 rpm & 32.4 ± 3.5 N) by 18 revolutions per minute and by 11.3 N, respectively.

The average heart rate during the uphill (175 ± 8 bpm) time trial was significantly greater than the level (173 ± 6 bpm) time trial (p = 0.021). Using the power versus heart rate relationship established in the laboratory, the difference in heart rate would account for a mean difference of 5.9 watts, which is significantly smaller than the 20-watt difference actually measured. The maximal heart rate measured during the uphill (184 ± 8 bpm) time trial was significantly greater than the level (180 ± 6.3) by an average of 4 beats (p = 0.007). Compared to the maximal heart rate measured in the laboratory (183 ± 8), the maximal heart rate measured during the uphill time trial was significantly greater by an average of 1 beat (p = 0.035). This difference, however, is likely due to the difference in the heart rate sampling interval in the laboratory (15 seconds) versus the field (1.26 seconds). Despite a maximal heart rate during the level time trial that was on average 3 beats lower than that measured in the laboratory, no significant difference was found between the two (p = 0.598). The maximal heart rate in the laboratory, however, was significantly correlated to both the uphill (r = 0.798, p < 0.001) and level (p = 0.840, p < 0.001)
maximal heart rate. These differences No difference was found between the minimum heart rates \( (p = 0.151) \) measured or the standard deviation \( (p = 0.619) \) of heart rates measured between the uphill versus the level time trial.

The perceived exertion measured on a 6-20 Borg scale immediately after each time trial was significantly greater in the uphill \( (18.3 \pm 1.1) \) compared to the level \( (17.4 \pm 1.3) \) time trial \( (p = 0.006) \).

A graphical display of power, power to weight (uphill only), power to drag area (level only), heart rate, speed, and cadence versus distance (km) for both the uphill and level time trial are presented in figure 4-1. For each respective time trial, the subjects displayed include the slowest and fastest individual as well as the group average. The data was graphed in 1.26-second intervals with a line fit over the data using a 2% smoothing factor.

The distribution of time (min:sec) for the uphill and level time trial was calculated using both heart rate and power relative to LT 1 mM (LT) and \( \text{VO}_2 \) peak. Results are presented in Table 4-5.

Three intensity ranges were used relative to LT and included the time below a heart rate reserve or power output associated with LT \(< 90\% \) of LT), time at LT \((90 \text{ to } 110\%\) ), and time above LT \( (> 110\%\) ). By power, 6.6\%, 21.5\%, and 71.9\% of the time on the uphill was spent below, at, and above LT, respectively, whereas the distribution on the level was 19.1\%, 23.2\%, and 57.7\% of total time. By heart rate, 1.1\%, 3.0\%, and 96.0\% of the time uphill was spent below, at, and above LT, whereas the distribution on the level was 1.7\%, 4.3\%, and 94.0\% of total time. Using power output as the measure of intensity, significant difference was found between
Figure 4-1. Absolute power, power to weight (uphill), power to drag (level), heart rate, speed, and cadence vs. distance during the uphill and level time trial. Data displayed is for the mean, the fastest individual in both the uphill and level time trial and the slowest individual in both time trials. A 2\% smoothing factor was used for all data displayed.
Table 4-5. Mean ± SD, minimum, and maximum values for time spent in discrete intensity ranges. The distribution for these ranges calculated from power and heart rate using lactate threshold and VO₂ as reference points are presented along with a distribution based on power to weight.
<table>
<thead>
<tr>
<th></th>
<th>Uphill Time Trial (9.09 km)</th>
<th></th>
<th>Level Time Trial (22.10 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Avs ± SD</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>From Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below LT (min)</td>
<td>02:05 ± 01:36 †*</td>
<td>00:09</td>
<td>05:08</td>
</tr>
<tr>
<td>At LT (min)</td>
<td>06:43 ± 03:13 ††*</td>
<td>00:36</td>
<td>14:36</td>
</tr>
<tr>
<td>Above LT (min)</td>
<td>22:32 ± 03:49 ††*</td>
<td>17:16</td>
<td>31:36</td>
</tr>
<tr>
<td>From Heart Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Below LT (min)</td>
<td>00:20 ± 00:13 †*</td>
<td>00:00</td>
<td>01:03</td>
</tr>
<tr>
<td>At LT (min)</td>
<td>00:56 ± 01:11</td>
<td>00:01</td>
<td>03:50</td>
</tr>
<tr>
<td>Above LT (min)</td>
<td>30:04 ± 03:28 †</td>
<td>23:42</td>
<td>38:51</td>
</tr>
<tr>
<td>From Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-50% of VO₂ peak</td>
<td>00:18 ± 00:06 †*</td>
<td>00:00</td>
<td>03:12</td>
</tr>
<tr>
<td>50-70% of VO₂ peak</td>
<td>02:18 ± 03:01 ††*</td>
<td>00:09</td>
<td>13:24</td>
</tr>
<tr>
<td>70-90% of VO₂ peak</td>
<td>13:47 ± 03:17 †*</td>
<td>09:28</td>
<td>20:54</td>
</tr>
<tr>
<td>&gt;90% of VO₂ peak</td>
<td>14:56 ± 04:29 ††*</td>
<td>07:26</td>
<td>23:06</td>
</tr>
<tr>
<td>From Heart Rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-50% of VO₂ peak</td>
<td>00:12 ± 00:06 †*</td>
<td>00:00</td>
<td>00:28</td>
</tr>
<tr>
<td>50-70% of VO₂ peak</td>
<td>00:08 ± 00:05</td>
<td>00:00</td>
<td>00:15</td>
</tr>
<tr>
<td>70-90% of VO₂ peak</td>
<td>06:44 ± 08:57 †*</td>
<td>00:09</td>
<td>39:09</td>
</tr>
<tr>
<td>&gt;90% of VO₂ peak</td>
<td>24:17 ± 07:41 †*</td>
<td>00:00</td>
<td>32:04</td>
</tr>
</tbody>
</table>

† Significantly different from the level time trial (p < 0.05).
* Significantly different from heart rate (p < 0.05).
the uphill and level below LT (p = 0.013), at LT (p < 0.001), and above LT (p < 0.001). Using heart rate as the measure of intensity significant difference was found below LT (p < 0.001) and above LT (p = 0.049), but not at LT (p = 0.221). When comparing power with heart rate, significant difference was found for all three intensity ranges on the uphill and on the level (p < 0.001) with heart rate underestimating time below LT and time at LT, and over-estimating time above LT.

Four intensity ranges were used relative to VO₂ peak using the power versus oxygen consumption or heart rate versus oxygen consumption relationship established in the laboratory. The intensity ranges included 0 to 50%, 50 to 70%, 70 to 90%, and greater than 90% of VO₂ peak. By power the distribution across these four intensity ranges were 1.0%, 7.4%, 44.0%, and 47.7% of the total time uphill and 4.3%, 14.9%, 44.6%, and 36.2% of the total time on the level. By heart rate the distribution was 0.6%, 0.4%, 21.5%, and 77.5% of the total time uphill and 0.8%, 0.6%, 37.2%, and 61.4% of the total time on the level (Figure 4-2). Using power output as the measure of intensity, significant difference was found between the uphill and level from 0 to 50% (p <0.001), 50, to 70% (p = 0.001), and greater than 90% of VO₂ peak (p < 0.001), but not between 70 to 90% (p = 0.666). Using heart rate as the measure of intensity, significant difference was found between the uphill and level at 0 to 50% (p = 0.031), 70 to 90% (p = 0.028), and greater than 90% of VO₂ peak (p = 0.027), but not at 50 to 70% (p = 0.133). With respect to power versus heart, uphill significant difference was found at all intensity ranges (p < 0.01) except for 0 to 50% of VO₂ peak (p = 0.553) whereas on the level significant difference was found for all intensity ranges (p < 0.01), except for 70 to 90% of VO₂ peak.
Figure 4-2. The mean distribution of heart rate and power output as percentages of VO₂ peak during the uphill and level time trial.
Individual correlations were performed to predict the time and mean power output for the uphill and level time trial (Table 4-6). Although the correlation between uphill time and level time was significant ($r = 0.57$, $p < 0.01$), only 32% of the variability in uphill time was explained by the variability in level time. In contrast, the relationship between the mean uphill and level power output was much stronger and significant ($r = 0.90$, $p < 0.01$). The relationship between uphill versus level time and power are presented in figure 4-3.

Figure 4-4 displays the relationship between level time and uphill time relative to the mean power output as well as mean power output normalized to body weight and $k$. The ability to predict uphill time was best when power output was normalized to body weight ($r = -0.95$, $p < 0.001$) or total weight ($r = -0.95$, $p < 0.001$). The ability to predict level time was best when power output was normalized to either $k$ ($r = -0.92$, $p < 0.001$) or drag area ($r = -0.92$, $p < 0.001$). Of note, body weight ($r = 0.48$, $p = 0.04$) and total weight ($r = 0.52$, $p = 0.02$) alone were significantly related to uphill time, while $k$ ($r = 0.85$, $p < 0.001$) and drag area ($r = 0.85$, $p < 0.001$) alone were significantly related to level time.

Of the physiological variables measured, $VO_2$ peak (l·min$^{-1}$) ($r = 0.84$, $p < 0.001$), power at $VO_2$ peak ($r = 0.75$, $p < 0.001$), and power at LT 1 mM ($r = 0.85$, $p < 0.001$) were significantly correlated to uphill power output. Likewise, $VO_2$ peak (l·min$^{-1}$) ($r = 0.83$, $p < 0.001$), power at $VO_2$ peak ($r = 0.67$, $p < 0.001$), and power at LT 1 mM ($r = 0.69$, $p < 0.001$) were significantly correlated to level power. Figure 4-5 displays the relationship between uphill and level power versus power at $VO_2$ peak and power at LT 1 mM. These physiological measures, however, were not strongly
Table 4-6. Correlation coefficients (p-value) relating different physiological and physical variables to uphill and level performance time and power.
<table>
<thead>
<tr>
<th></th>
<th>Uphill Time</th>
<th>Level Time</th>
<th>Uphill Power</th>
<th>Level Power</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Uphill Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Level Time</strong></td>
<td>.57 (.01)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Uphill Power</strong></td>
<td>-.42 (.08)</td>
<td>-.40 (.09)</td>
<td>.90 (&lt;.01)</td>
<td></td>
</tr>
<tr>
<td><strong>Level Power</strong></td>
<td>.39 (.10)</td>
<td>-.59 (.01)</td>
<td></td>
<td>.90 (&lt;.01)</td>
</tr>
<tr>
<td><strong>Body Mass</strong></td>
<td>.48 (.04)</td>
<td>.05 (.84)</td>
<td>.55 (.02)</td>
<td>.49 (.03)</td>
</tr>
<tr>
<td><strong>Uphill Total Mass</strong></td>
<td>.52 (.02)</td>
<td>.11 (.67)</td>
<td>.55 (.02)</td>
<td>.51 (.03)</td>
</tr>
<tr>
<td><strong>Level Total Mass</strong></td>
<td>.43 (.07)</td>
<td>.12 (.628)</td>
<td>.57 (.01)</td>
<td>.56 (.01)</td>
</tr>
<tr>
<td><strong>K constant</strong></td>
<td>.63 (&lt;.01)</td>
<td>.85 (&lt;.01)</td>
<td>-.24 (.32)</td>
<td>-.32 (.18)</td>
</tr>
<tr>
<td><strong>A_d</strong></td>
<td>.63 (&lt;.01)</td>
<td>.85 (&lt;.01)</td>
<td>-.22 (.36)</td>
<td>-.32 (.17)</td>
</tr>
<tr>
<td><strong>A_p</strong></td>
<td>.46 (&lt;.05)</td>
<td>.47 (.04)</td>
<td>.19 (.43)</td>
<td>.08 (.73)</td>
</tr>
<tr>
<td><strong>C_d</strong></td>
<td>.34 (.16)</td>
<td>.64 (&lt;.01)</td>
<td>-.52 (.02)</td>
<td>-.54 (.02)</td>
</tr>
<tr>
<td><strong>Est A_p</strong></td>
<td>.41 (.08)</td>
<td>.03 (.91)</td>
<td>.60 (&lt;.01)</td>
<td>.53 (.02)</td>
</tr>
<tr>
<td><strong>Rolling Resistance</strong></td>
<td>.43 (.07)</td>
<td>.20 (.41)</td>
<td>.05 (.83)</td>
<td>.08 (.75)</td>
</tr>
<tr>
<td><strong>VO_2 peak (l min^-1)</strong></td>
<td>-.31 (.19)</td>
<td>-.42 (.08)</td>
<td>.84 (&lt;.01)</td>
<td>.83 (&lt;.01)</td>
</tr>
<tr>
<td><strong>VO_2 peak (ml kg^-1 min^-1)</strong></td>
<td>-.82 (&lt;.01)</td>
<td>-.52 (.02)</td>
<td>.14 (.56)</td>
<td>.20 (.42)</td>
</tr>
<tr>
<td><strong>VO_2 peak (power, watts)</strong></td>
<td>-.18 (.45)</td>
<td>-.43 (.07)</td>
<td>.75 (&lt;.01)</td>
<td>.67 (&lt;.01)</td>
</tr>
<tr>
<td><strong>LT (% of VO_2 peak)</strong></td>
<td>-.57 (.011)</td>
<td>-.20 (.412)</td>
<td>.45 (.056)</td>
<td>.28 (.250)</td>
</tr>
<tr>
<td><strong>LT (power, watts)</strong></td>
<td>-.46 (&lt;.05)</td>
<td>-.45 (.06)</td>
<td>.85 (&lt;.01)</td>
<td>.69 (&lt;.01)</td>
</tr>
<tr>
<td><strong>Economy (watts l O_2^-1)</strong></td>
<td>-.39 (.10)</td>
<td>-.11 (.67)</td>
<td>.07 (.78)</td>
<td>-.17 (.48)</td>
</tr>
</tbody>
</table>

**Uphill Power to Body Mass** | -.95 (<.01) |

**Uphill Power to Total Mass** | -.95 (<.01) |

**Level Power to Body Mass** | -.59 (<.01) |

**Level Power to Total Mass** | -.68 (<.01) |

**Uphill Power to k** | -.67 (.002) |

**Uphill Power to A_d** | -.68 (.001) |

**Uphill Power to A_p** | -.70 (.001) |

**Uphill Power to C_d** | -.39 (.101) |

**Uphill Power to Est A_p** | -.88 (.000) |

**Level Power to k** | -.92 (.000) |

**Level Power to A_d** | -.92 (.000) |

**Level Power to A_p** | -.75 (.000) |

**Level Power to C_d** | -.69 (.001) |

**Level Power to Est A_p** | -.71 (.001) |

**Power at VO_2 peak to B. Mass** | -.73 (.000) |

**Power at VO_2 peak to k** | -.62 (.005) |

**Power at LT 1 mM to B. Mass** | -.82 (.000) |

**Power at LT 1 mM to k** | -.66 (.002) |
Figure 4-3. The relationship between uphill time versus level time and uphill power versus level power for all 19 subjects. Although a significant correlation ($p < 0.01$) was found for both relationships, the relationship between uphill and level power ($p = 0.90$) was significantly greater ($p < 0.001$) than that found between uphill and level time ($r = 0.57$).
Uphill Time (Sec)

\[ y = 204.44 + 0.88958x \quad R = 0.56721 \quad p = 0.011 \]

Level Time (Sec)

\[ y = 22.682 + 0.99204x \quad R = 0.89627 \quad p < 0.0001 \]
Figure 4-4 displays the relationship between level time and uphill time relative to the mean power output as well as mean power output normalized to body weight and $k$. 
Figure 4-5 displays the relationship between uphill and level power versus power at VO₂ peak and power at LT 1 mM.
Power at \( VO_2 \) max (Watts)

- \( y = 56.149 + 0.74057x \) \( R^2 = 0.75174 \) \( p < .0001 \)
- \( y = 39.13 + 0.59335x \) \( R^2 = 0.66666 \) \( p = .002 \)
- \( y = 91.012 + 0.85807x \) \( R^2 = 0.85129 \) \( p < .0001 \)
- \( y = 134.14 + 0.6246x \) \( R^2 = 0.68589 \) \( p = .001 \)

Power at LT (Watts)

- \( y = 91.012 + 0.85807x \) \( R^2 = 0.85129 \) \( p < .0001 \)
- \( y = 134.14 + 0.6246x \) \( R^2 = 0.68589 \) \( p = .001 \)
related to uphill or level time. But, when normalized to body weight, VO2 peak (ml·kg⁻¹·min⁻¹) (r = -0.82, p < 0.001), power at VO2 peak (watts·kg⁻¹) (r = -0.73, p < 0.001), and power at either LT 1 mM (r = -0.82, p < 0.001) were strongly correlated to uphill time. Likewise, when normalized to k, power at VO2 peak (watts·N⁻¹·V²) (r = -0.92, p < 0.001), and power at either LT 1 mM (r = -0.85, p < 0.001) were strongly correlated to level time. Figure 4-6 displays the relationship between uphill and level time versus power at VO2 peak and power at LT 1 mM in absolute terms and when normalized to body weight and k.

Rolling resistance alone or when used to normalize power or physiological measures was not related to uphill or level time. Likewise, economy was not related to either uphill or level time and power.

Stepwise regression was also performed to predict uphill and level time and power. For the prediction of uphill time if all variables measured in the laboratory and uphill time trial are used, the best predictor of uphill time is the uphill power to total weight, with all other variables excluded (r = -0.98, p < 0.001, y = -433.353 x uphill power to total weight + 3644.011). When only laboratory variables are used (VO2 peak in l O2·min⁻¹, VO2 peak in ml·kg⁻¹·min⁻¹, LT as a % of VO2 peak, and economy), the combination of VO2 peak in ml·kg⁻¹·min⁻¹ and economy best predict uphill time (r = 0.88, p < 0.001, y = -20.79 x VO2 ml·kg⁻¹·min⁻¹ + -17.57 x economy + 4576.22). If VO2 peak and LT are expressed as a power output and normalized to resistance variables, the best predictor of uphill time is power at LT 1 mM normalized to weight with all other variables excluded (r = -0.82, p < 0.001, y = -282.58 x power to weight at LT 1 mM + 2974.10).
Figure 4-6 displays the relationship between uphill and level time versus power at VO$_2$ peak and power at LT 1 mM in absolute terms and when normalized to body weight and k.
For the prediction of uphill power output, if we include all variables measured in the laboratory, the best predictors are power at LT 1 mM and VO$_2$ peak (1·min$^{-1}$) \( (r = 0.904, p < 0.001, y = 0.51 \times \text{power at LT 1 mM} + 33.85 \times \text{VO}_2 \text{ peak} + 28.49) \).

For the prediction of level time if all variables measured in the laboratory and level time trial are used the best predictors of level time are the level power to drag area \( (r = 0.926, p < 0.001, y = -0.53 \times \text{level power to drag area} + 2358.57) \). The correlation coefficient, however, for this relationship is not significantly different from level power to k \( (r = -0.924, p < 0.001) \). When only laboratory variables are used \( (\text{VO}_2 \text{ peak in } l \text{ O}_2 \cdot \text{min}^{-1}, \text{VO}_2 \text{ peak in } ml\cdot kg^{-1} \cdot \text{min}^{-1}, \text{LT} \text{ as a } \% \text{ of } \text{VO}_2 \text{ peak}, \text{and economy}) \), VO$_2$ peak in ml·kg$^{-1}$·min$^{-1}$ is the best predictor of level time \( (r = 0.516, p = 0.024, y = -8.59 \times \text{VO}_2 \text{ peak in } ml\cdot kg^{-1} \cdot \text{min}^{-1} + 2464.26) \). If VO$_2$ peak and LT are expressed as a power output and normalized to resistance variables, the best predictor of level time is power at VO$_2$ peak normalized to k \( (r = 0.921, p < 0.001, y = -0.24 \times \text{Power at VO}_2 \text{ peak to k} + 2391.33) \). This correlation is not significantly different from that obtained using the actual level power normalized to drag area or k.

For the prediction of level power output, using all the variables measured in the laboratory, the best predictor is VO$_2$ peak \( (l\cdot min^{-1}) \) \( (r = 0.83, p < 0.001, y = 54.67 \times \text{VO}_2 \text{ peak} + 48.27) \).

**Discussion**

As hypothesized, a cyclist's power output normalized to total mass (body + bicycle) or body mass is the best predictor of uphill performance time \( (r = -0.95, p < 0.001) \), while a cyclist’s power output normalized to a true representation of
aerodynamic resistance (i.e., k or A_d) is the best predictor of level performance time (r = -0.92, p < 0.001). These results demonstrate and confirm the distinct contribution of gravitational and aerodynamic resistance imposed by uphill and level terrain. More importantly, the significantly lower correlation between uphill and level performance time (r = -0.57, p < 0.05) compared to uphill and level power output (r = 0.90, p < 0.001), illustrates the critical and distinct role that these forms of resistance play on performance. Accordingly, physiological indices of performance, though significantly correlated to field power output (r = 0.69 to 0.85), were poorly related to uphill and level performance time (r = -0.11 to -0.57), unless normalized to body weight or aerodynamic resistance (r = -0.73 to -0.92), respectively. Of note, the relationship between these physiological measures and performance time on the level was not better than our measures of aerodynamic resistance alone (r = 0.85, p < 0.001), suggesting that in our population physiological measures of performance are more homogeneous than aerodynamic measures. In contrast, rolling resistance was not a distinguishing performance factor uphill or on the level. Finally, for the same duration, the average power output was significantly higher uphill compared to the level (324 vs. 303 watts).

The finding that uphill performance time was best predicted by normalizing field power output to total mass or body mass is not surprising and agrees with others who have demonstrated that uphill cycling performance is a function of a cyclist’s power to weight ratio (1, 19, 35, 38, 48, 62). On our particular course, 87% of the total power requirement was due to gravitational resistance. The average power output measured during the actual time trial was not related to uphill time (r = -0.42,
p > 0.05), showcasing the strong influence of mass and gravitational resistance on uphill performance. Because the actual gravitational resistance is determined by the total mass of the bicycle and rider system, it has been suggested that the addition of bicycle (mean ± SD: 9.0 ± 0.90 kg) to body mass (70.8 ± 8.0 kg) is a better predictor of uphill performance (35). We did not, however, find any difference in our ability to predict uphill performance using either power output normalized to body mass (r = -0.95) or total mass (r = -0.95), both of which explained 90% of the variability in uphill time. Of note, body mass was significantly and positively correlated to uphill performance time (r = 0.48, p < 0.05), explaining 23% of the variability in uphill time. Thus, our heavier riders tended to ride slower times than the lighter riders, despite the fact that they tended to produce more absolute power. This agrees with the idea that an increase in power output from a given increase in muscle mass is typically not enough to equal or overcome that additional mass, resulting in a lower power to weight ratio (62, 68, 69). Normalized to body weight, our subjects averaged 4.61 watts·kg	extsuperscript{-1} during the uphill time trial, with our slowest rider at 3.52 watts·kg	extsuperscript{-1} and our fastest rider at 5.21 watts·kg	extsuperscript{-1}. Using a regression between ascent rate and power to weight (r = -0.95, p < 0.001), at a fixed velocity on this particular course every additional kilogram of mass increased the energy cost of the climb by 3.6 watts. So for our slowest rider to match our fastest rider uphill, the slowest rider would have to improve their absolute power output by approximately 100 watts or decrease their body weight by approximately 26 kg. Furthermore, if our heaviest (89 kg) and lightest (59 kg) rode at an equivalent ascent rate of 1400 m·hr	extsuperscript{-1} (≈ 5 watts·kg	extsuperscript{-1}), then
their absolute power requirement would be 444 watts vs. 295 watts, respectively – a difference of 149 watts.

Although small, the unexplained variance in uphill time could be due to a number of factors, including differences in the individual pacing strategy, wind and/or environmental conditions, resistance associated with changes in kinetic energy (i.e., accelerations), changes in the actual versus measured body position while climbing, aerodynamic resistance, rolling resistance, and variability in the power meters used (50, 70). While all may have affected performance, we were only able to directly evaluate the impact of aerodynamic resistance, rolling resistance, and the power meters used.

It has been shown previously that the Power Tap power meter is accurate and reliable within and between units (25, 28). This was confirmed by evaluating each power meter used in this study against a torque dynamometer prior to testing. Thus, we do not believe that that variability within or between power meters affected our results.

In contrast, we initially suspected that the additional variance in uphill performance time could be explained by differences in aerodynamic resistance. This was spurred by the finding that for the upright or assumed uphill body position, $k_{up}$ and $A_{du}^{up}$ were both significantly and positively correlated to uphill time ($r = 0.63$, $p < 0.01$), despite only accounting for 7.41% of the required power output uphill. The addition of $k_{up}$ and $A_{du}^{up}$ in a stepwise regression, however, did not improve the prediction of uphill performance time compared to power normalized to total weight alone. Further analysis revealed a small shared variance between body weight and
both projected frontal area \( r = 0.61, p < 0.05 \) and \( k_{up} \) \( r = 0.53, p < 0.05 \). Thus, the
correlation between aerodynamic resistance and uphill time may be strongly
influenced by the impact of mass on aerodynamic resistance (33, 38, 69). To account
for the relationship between mass and aerodynamic resistance and their combined
effect on uphill cycling, it has been suggested that power or a correlate of power
should be normalized to body weight raised to an exponent of 0.79 or 0.89 (34, 69).
In our study, scaling body mass or total mass with these exponents worsened our
prediction of uphill performance time. Similar to Padilla et al., who examined
climbing performance in European professionals, we found that a body mass
exponent of 1.0 provided the best correlation to uphill time trial performance (62).
While we cannot discount the impact of aerodynamic resistance on uphill
performance, on this particular course with our particular riders, aerodynamic
resistance does not appear to be a distinguishing factor.

Rolling resistance, which accounted for 5.24% of the average total power
requirement uphill, was not related to uphill performance time using either bivariate
or stepwise regression. Since we held tire pressure constant with all of our subjects
riding similar style and width (23 to 25 mm) clincher tires, the most logical reason for
this finding is that the coefficient of rolling resistance between subjects was relatively
constant and that differences in rolling resistance were merely a function of the total
mass (30, 66).

Indirectly, there is evidence that differences in the environment and or wind
conditions may have played a role in the uphill performance. In a subset of eight
subjects who all performed the uphill time trial on the same day under equivalent
environmental and wind conditions, the correlation between performance time and power to total mass ($r = -0.98$, $p < 0.001$), was significantly greater than same correlation in a subset of the remaining 11 subjects ($r = -0.91$, $p < 0.001$). Because we cannot be sure that the wind and environmental conditions were the same between the nine different days that the uphill time trial was performed, it is reasonable that the environment played a role on the performance outcome.

A large number of studies have explored techniques for quantifying aerodynamic resistance during cycling (11, 12, 18, 20, 23, 31, 39, 41, 50, 61, 65). Many others have developed mathematical models exploring the hypothetical performance impact of these measures (5, 9, 21, 22, 54-57, 59, 60). Though all would agree that aerodynamics along with one’s ability to supply power is the critical determinant of level cycling performance, the simultaneous measurement of power output during a level time trial in the field along with the individual assessment of aerodynamic drag has never been performed. Thus, our finding that level performance time is best predicted by normalizing field power output to either $k$ or $Ad$ ($r = -0.92$, $p < 0.001$), while perhaps self-evident, is truly unique and underscores the significant absence of aerodynamic measures in studies attempting to predict cycling performance. Moreover, the average field power, though significantly correlated to level time ($r = -0.59$, $p < 0.01$), only explained $35\%$ of the variability in level time versus $85\%$ when normalized to aerodynamics. In the only other study to measure field power output during a level time trial, Balmer et al. did not find a significant correlation between the average field power and performance time ($r = 0.46$, $p > 0.05$) (2). Furthermore, in professional cyclists Padilla et al., did not find a
distinct physiological attribute distinguishing the field performance of level time trialists, suggesting that differences in aerodynamics must be a critical performance determinant (62).

By itself, aerodynamic drag represented as either $k$ or $Ad$, was significantly correlated to performance time ($r = 0.85$, $p < 0.001$), explaining 72% of the variability in performance time. Thus, it appears our subject’s ability to produce power was more homogeneous than their aerodynamic character, making aerodynamics a better predictor of performance than power production. The relative heterogeneity in aerodynamics, however, may have been artificially imposed by the various body positions and equipment used by our subjects. In fact, we did not control for the body positions or equipment used during the level time trial in an attempt to create as fair of an appraisal of a normal performance in our population as possible. Instead, we simply asked our subjects to use the equipment and position they would normally use in a level time trial. In turn, out of our nineteen subjects, eleven used time trial bicycles, four used standard road bicycles with aerodynamic handlebars, and the remaining four used a standard road bicycle with no specific aerodynamic equipment. Though each group had significantly different mean values for $Ad$, within the eleven subjects using time trial bicycles our results were similar with power normalized to aerodynamics the single best predictor of performance time ($r = -0.90$, $p < 0.001$), aerodynamics the next best predictor ($r = 0.76$, $p < 0.001$), and power not predicting performance time ($r = -0.30$, $p > 0.05$).

Aerodynamics, however, is not always more important than power. For example, in a group of elite amateur European cyclists, a significant correlation was
found between peak power production in the laboratory and level time trial performance \((r = -0.90, p < 0.05)\), demonstrating a situation where aerodynamics did not play a strong role in performance (1). In addition, a number of studies using a heterogeneous population pool have shown significant correlations between physiological capacity in the laboratory and field time trial performance (REFS) (32, 35, 37, 53, 63, 67).

The assumption, however, that aerodynamic drag is similar between individuals is also incorrect. Using coast down tests in seven subjects, De Groot et al., found a mean \((\pm SD) A_d\) of 0.32 ± 0.04 with a range from 0.28 to 0.38 m\(^2\) in seven subjects while they rode in a dropped position (20). Similarly, in a previous study we found a mean \(A_d\) of 0.32 ± 0.06 with a range of 0.27 to 0.44 m\(^2\) in eight subjects while in a dropped position (44). In the present study, the mean \(A_d\) associated with the level time trial was 0.34 ± 0.06 with a range of 0.26 to 0.46 m\(^2\). To give some perspective to these values, at the average velocity held during the level time trial (42.4 km·hr\(^{-1}\)) and in a similar environment (Air density = 0.97 kg·m\(^{-3}\)), the mean power needed to overcome aerodynamic resistance would be 252 ± 28 watts (range: 223 to 300 watts) using De Groot’s data, 254 ± 48 watts (range: 214 to 349 watts) using our previous data, and 269 ± 48 watts (range: 206 to 364 watts) in the present study. In contrast, the actual power measured during the level time trial was 303 ± 26 watts (range: 259 to 354). Thus, the variability (SD; 26 vs. 48 watts, range: 95 vs. 158 watts) in power at a given speed resulting from aerodynamic resistance is almost twice that of the actual measured power in our population. Ultimately, to adequately predict level time trial performance, assumptions should not be made about either aerodynamics or
power production since both can be highly heterogeneous or homogeneous depending upon the given population. Rather, both power and aerodynamic drag should be measured individually and should, as in our study, produce the best prediction of level performance.

Because aerodynamic drag has been difficult to measure in the past, many studies have attempted to use estimates of the projected frontal area (Est \( A_p \)) or actual measures of projected frontal area (\( A_p \)) to represent aerodynamic drag (33, 58-60, 69). Since aerodynamic resistance is a function of the \( A_p \), coefficient of drag, the environment, and velocity, this assumes that in a given environment at a given speed that the coefficient of drag is similar between individuals and that the \( A_p \) is the primary determinant of \( k \) or \( Ad \). There are, however, specific examples that contradict this idea (20, 39). Accordingly, we found that the correlation to level time was significantly lower using power normalized to \( A_p \) or Est \( A_p \) compared to power normalized to either \( k \) or \( Ad \) (\( r = -0.75 \) and -0.71 vs. -0.92). In addition, these correlations were not different than those found using power (\( r = -0.59 \)) or \( k \) (\( r = -0.85 \)) alone. By itself, \( A_p \) explained 22% of the variability in level time, while Est \( A_p \) explained none. Interestingly, \( A_p \) was correlated to \( k \) and \( A_d \) (\( r = 0.72, p < 0.01 \)), but Est \( A_p \) was not (\( r = 0.23, p > 0.05 \)), which raises questions about the correlation between level time and power normalized to Est \( A_p \). Finally, no relationship was found between \( A_p \) and the coefficient of drag (\( r = -0.16, p > 0.05 \)) demonstrating their independence and individual importance in determining \( k \) and \( Ad \). From these findings it appears that an actual or estimate of projected area, does not explain all of
the variability in aerodynamic resistance and when used to normalize power is not necessarily better in the prediction of level time than power or k alone.

Like the uphill time trial, the unexplained variance during the level time trial could be due to differences in the individual pacing strategy, wind and/or environmental conditions, resistance associated with changes in kinetic energy (i.e., accelerations), and changes in the actual versus measured body position while cycling. Although rolling resistance comprised a higher percentage of the total resistance while cycling on the level (10.23%) compared to uphill (5.24%), no relationship was found between rolling resistance and level time. More than likely, we believe that subtle differences in wind conditions played a role on performance. Again, evidence for this is indirect and is based on the finding that in a subset of eight subjects who all performed the level time trial on the same day under equivalent environmental conditions, the correlation between performance time and power normalized to k or Ad ($r = -0.98$, $p < 0.001$) was significantly greater than the same correlation in a subset of the remaining 11 subjects ($r = -0.90$, $p < 0.001$).

The finding that uphill and level times were not highly correlated ($r = 0.57$, $p < 0.05$) despite an extremely strong relationship between the average uphill and level power outputs ($r = 0.90$, $p < 0.001$) further supports the importance of gravitational and aerodynamic resistance on performance. More importantly, this data demonstrates that, with respect to predicting level versus uphill performance, body mass and aerodynamics are relatively independent attributes. In fact, on the level body mass and aerodynamics were not related in this study ($r = 0.27$, $p < 0.05$). Though, a decrease in mass can decrease aerodynamic drag within an individual (38,
our data shows that between individuals aerodynamic drag cannot be predicted from mass. Ultimately, a cyclist’s performance uphill does not necessarily predict their performance on the level since the attributes that determine uphill and level performance are distinct.

Though there was no significant difference in the mean uphill versus level time, the mean power output was significantly greater uphill compared to the level for every individual (324 vs. 303 watts). While a more upright body position and steeper road angle could theoretically elicit a physiological and/or biomechanical advantage uphill (29, 51), it is more likely that to maintain momentum uphill and because of pauses while cornering on the level, subjects were simply more consistent in their application of power during the uphill time trial. For example, uphill an average of 2.21± 3.63 seconds was spent at zero watts versus 30.6 ±11.3 seconds for the level. On the level, if this difference (28.4 sec) was spent at each subject’s lactate threshold rather than at zero watts, then the average power on the level would increase by 10 watts or close to half of the measured power difference. In actuality, however, when the average power output on the level was calculated excluding the time at zero watts, the average power output only increased by 2 watts. This is because subjects also spent significantly more time below their lactate threshold on the level, which in itself explains most of the discrepancy in power. In fact, the absolute power difference between the uphill and level time trial was significantly correlated to time spent below LT in the level time trial (r = 0.83, p < 0.001), but not correlated to time at zero watts in the level time trial (r = -0.30, p > 0.05). Given the significantly slower speed, lower cadence, and higher torque while riding uphill, any pause or drop in power
would immediately result in a marked decrease in velocity and require a significant increase in torque to regain momentum. This would not be the case on the level. Thus, it is unlikely that the power difference was due to some inherent physiological or biomechanical mechanism but simply due to a difference in the distribution of power output.

From our results, it is clear that the actual power output normalized to body weight best predicts uphill cycling time, and that the actual power output normalized to a measure of aerodynamic drag best predicts level cycling time. Because power output cannot always be measured in the field and since predicting a cyclist's performance potential a priori can be valuable, we were also interested in how well common physiological measures of endurance performance from the laboratory correlated with the actual field power. Our assumption is that if a physiological measure correlates highly with the field power output, then that measure normalized to body weight or to aerodynamic drag would also correlate highly to uphill or level performance time, respectively.

Even without an assessment of aerodynamics, a number of investigators have shown strong and significant correlations ($r = -0.69$ to $-0.98$) between laboratory measures of performance, such as VO$_2$ max, peak power output, the lactate threshold or ventilatory threshold, and economy, with level time trial performance in the field ($32, 37, 49, 53, 63, 67$). Although evidence exists that aerodynamic drag can be quite variable between individuals ($20, 44$), it is likely that in these studies aerodynamic drag was relatively homogeneous compared to laboratory performance measures, especially since the subjects in some these studies varied widely in fitness level ($32, 63$).
37, 63, 67). This heterogeneity, when combined with small subject numbers, could further affect these observed correlations. In contrast, in very elite populations access to aerodynamic equipment and careful attention to body position could make power production a better predictor of performance (1). These findings, however, do not necessarily contradict our own. Rather, it is our belief that the results from these previous studies would be much stronger if aerodynamic measures were available. This is especially true since a number of studies using fairly homogeneous populations did not find a relationship between absolute laboratory measures and field performance (2, 36, 62). In fact, we found that \( \text{VO}_2 \) peak (\( \text{l}\cdot\text{min}^{-1} \& \text{watts} \)), LT (% of \( \text{VO}_2 \) peak & watts), and economy were not significantly correlated to level time trial performance (\( r = -0.11 \) to -0.43, \( p < 0.05 \)). Accordingly, for the purpose of this discussion we will focus primarily on how our laboratory performance measures predict uphill and level field power.

In our study the absolute oxygen cost (\( \text{l}\cdot\text{min}^{-1} \)) or power output associated with \( \text{VO}_2 \) peak was significantly correlated to both uphill (\( r = 0.75 \& 0.84, p < 0.01 \)) and level (\( r = 0.67 \& 0.83, p < 0.01 \)) field power output, with no significant difference between the observed correlation coefficients (i.e., \( \text{l}\cdot\text{min}^{-1} \) vs. watts or uphill vs. level). Of note, \( \text{VO}_2 \) peak normalized to body weight was not correlated to field power output, though it was highly predictive of uphill performance time (\( r = -0.82, p < 0.05 \)) and explained some of the variability in level performance time (\( r = -0.52, p < 0.05 \)). In contrast to our findings, Balmer et al., who also measured field power output during a 16.1 km level time trial, found a significantly higher correlation between peak power and average field power (\( r = 0.99, p < 0.05 \)) (2). Our results, however, are
not significantly different from other studies that have compared the relationship between VO2 max or peak power and average power output or finishing time during simulated laboratory time trials ranging in length from 50 to 90 minutes (r = 0.53 to 0.91) (6, 8, 43). Although, the higher correlation found by Balmer et al. may be due to their shorter time trial, Bentley et al. actually showed a significantly lower correlation between peak power output and average power output during a 20 minute time trial (r = 0.54, p < 0.05), concluding that peak power was a better predictor of longer time trials (2, 6). Regardless, we would not suspect that VO2 peak would be a perfect predictor of performance power since VO2 peak can be independent of other physiological attributes like the lactate threshold or economy which may also affect a cyclist's sustainable power output (4, 14, 46).

The correlation between LT power and uphill (r = 0.85, p < 0.01) or level (r = 0.69, p < 0.01) power was the same as that found for VO2 peak. While the LT is the best predictor of cycling performance in populations matched for VO2 max (15, 16, 46), if VO2 max is not controlled for, the relationship between LT power and average power during simulated laboratory simulations are similar to those found in this study (6, 7, 43). Of note, the relationship between uphill and level power output when power was expressed as a % of LT (r = 0.90, p < 0.05) was significantly better than if power was expressed as a % of VO2 peak (r = 0.81, p < 0.05). Thus, in and of itself, the LT does not appear to be a significantly better predictor of the absolute uphill or level power compared to VO2 peak, but may be a better predictor of the relative pace.

We found no correlation between economy (watts·1 O2·l) and uphill (r = 0.07, p > 0.05) or level (r = -0.17, p > 0.05) time trial performance. This was also true if we
expressed economy as the gross mechanical efficiency or as delta efficiency. Although, Malhorta et al. did find a strong relationship between submaximal oxygen cost at 150 watts and level time trial performance in the field ($r = 0.85$, $p < 0.05$), most studies have not shown economy to be a strong independent predictor of endurance performance (49). Rather economy is thought to be important to endurance performance in elite populations matched for $V_{02\ max}$ or similarly performing cyclists with varying $V_{02\ max}$ (15, 16, 47). We did not, however, find that economy improved our ability to predict uphill or level power when used in conjunction with $V_{02\ peak}$ or the LT during stepwise regression.

If economy is calculated, as it is in swimming or running, as the oxygen cost for a given velocity rather than as the oxygen cost for a given power output, the large differences in aerodynamic drag in our population would make economy a critical determinant of actual level performance time. As an example, at a constant velocity of 40 km·hr$^{-1}$ and fixed economy of 73.5 watts·l·$O_{2}$·min$^{-1}$, the mean oxygen cost calculated from each individual’s value for $k$, would be $4.00 \pm 0.64$ l·min$^{-1}$ with a range of 2.82 to 5.41 l·min$^{-1}$. In contrast, at a constant power output of 293 watts (the average for 40 km·hr$^{-1}$), the mean oxygen cost calculated from each individual’s value for economy, would be $3.99 \pm 0.17$ l·min$^{-1}$ with a range from 3.72 to 4.24 l·min$^{-1}$. Based on these figures, the standard deviation in oxygen cost for a given velocity would be close to 4 times greater than the oxygen cost for a given power output while the range would be 5 times greater. Thus, while our results show that economy determined in the laboratory does not influence the power output well trained cyclists can maintain in
the field, economy, expressed as the oxygen cost per velocity, would be a critical determinant of performance.

Using stepwise regression, uphill power was best predicted by the combination of power at LT and \( \text{VO}_2 \) peak (l\cdot\text{min}^{-1}) \((r = 0.90, p < 0.05)\), while level power was best predicted only by \( \text{VO}_2 \) peak (l\cdot\text{min}^{-1}) \((r = 0.83, p < 0.05)\). This was unusual since we did not find power at LT to be independent of \( \text{VO}_2 \) peak (l\cdot\text{min}^{-1}) \((r = 0.72, p < 0.05)\). At the same time, we did find that \( \text{VO}_2 \) peak (l\cdot\text{min}, ml\cdot\text{kg}^{-1}\cdot\text{min}^{-1}, watts), economy (watts\cdot l \text{O}_2^{-1}), and the LT measured as a % of \( \text{VO}_2 \) peak were all independent of one another \((r = -0.27 \text{ to } 0.446, p > 0.05)\). Accordingly, it was our thought that the latter combination would best predict performance power.

Nevertheless, our results from the individual regressions are similar to those found by others \((6, 8, 16)\). Furthermore, studies that have found the combination of \( \text{VO}_2 \) max, LT and economy to be predictive of laboratory time trial performance controlled for \( \text{VO}_2 \) max \((15, 16, 46)\).

Despite our strong results, there could be a number of reasons why performance measured in the laboratory is not a perfect predictor of field power output. First and foremost, a strong relationship between the field and laboratory depends on subjects giving truly maximal efforts during the laboratory test and time trials. While all subjects reached a RPE of 19 or 20 at the end of the laboratory stress test, the RPE data taken after each time trial was less consistent. In the uphill time trial, the mean RPE was \(18.3 \pm 1.1\) with a range from 16 to 20 and a mode of 19. In the level time trial, the mean RPE was significantly lower at \(17.4 \pm 1.3\) with a range of 14 to 20 and a mode of 17. In addition, the RPE values measured in the two time
trials were not significantly correlated to one another ($r = 0.45$, $p > 0.05$). These differences could also explain the wide range in intensity observed relative to the lactate threshold (uphill: 110 to 135%, level: 96 to 133% of LT power) and VO$_2$ peak (uphill: 75 to 96%, level: 70 to 93% of VO$_2$ peak power) during each time trial. On the other hand, this variation in relative intensity could simply reflect differences in physiological attributes not measured during the laboratory testing. Of note, anaerobic power or capacity has been shown to help improve performance prediction over variables like the lactate threshold or VO$_2$ max alone (10, 19). Given the relatively short duration of our time trials it is possible that differences in anaerobic function may have affected performance. This is especially true since the pattern of power output during the time trial was quite variable with a mean standard deviation calculated during each time trial of 55 watts uphill and 80 watts on the level. In addition, subjects surged above their power at VO$_2$ peak an average of 37 times (7 seconds per surge) uphill, and an average of 30 times (6 seconds per surge) on the level. Given the distinct physiological differences observed during steady state versus intermittent exercise (3), it is quite possible that our laboratory measures do not reflect the unique demands of field cycling, even in the time trial – an event that is normally thought of as a steady state activity. Finally, there may simply be an inherent difference between the physiological responses to graded exercise in the laboratory compared to those during a free-range task in the field (17, 26, 27, 71). Although, all of these factors would have affected how well our laboratory measures predicted the actual field power output, these factors would not have affected our prediction of performance time, since finishing time would still be relative to each
individual's field power and physical characteristics. As such, for an accurate assessment of performance it may be best to simply measure power production in the field rather than relying on physiological measures to predict power.

Based on the relationship between field power output and laboratory performance, when normalized to k or Ad, VO₂ peak power (r = -0.92, p < 0.001) is as strong of a predictor of level performance time as the actual level power output (r = -0.92, p < 0.001). In contrast, LT power (r = -0.85, p < 0.001) is a strong but significantly weaker predictor of level performance compared to both VO₂ peak and level power when all are normalized to k or Ad. As expected uphill power (r = -0.95, p < 0.001) is a significantly better predictor of uphill performance time compared to VO₂ peak (r = -0.73, p < 0.001) and LT power (r = -0.82, p < 0.001) when all are normalized to mass, with no difference between VO₂ peak and LT power. Though we have no direct explanation for the differences observed between the uphill and level time trial, these findings may be due to the pauses in power observed during the level time trial. It is possible that the more consistent application of power and the higher average power output in the uphill time trial make the results from the uphill time trial more relevant than those from the level time trial.

In conclusion, to predict cycling performance in the field a cyclist's ability to produce power must be considered relative to the forces that resist forward motion. Accordingly, level time trial performance is best predicted by normalizing the actual level power output to aerodynamic resistance per velocity squared (k) or the drag area (Ad). Similarly, uphill time trial performance is best predicted by normalizing the actual uphill power output to body or total mass. Though power at VO₂ peak or LT
are not perfect predictors of field power, if power cannot be measured in the field, these variables when normalized to aerodynamic drag on the level or mass uphill, are still better predictors of field performance compared to field power alone. Moreover, despite the fact that physiological variables are commonly thought of as the most important determinant of performance, we found that alone, measures of aerodynamic resistance were better related to level performance than VO₂ peak, LT, or economy. Finally, neither economy nor rolling resistance improve the prediction of uphill or level time trial performance.
References V


CHAPTER VI: SUMMARY AND CONCLUSIONS

Compared to metabolic measures on a standard laboratory ergometer and first principle mechanical testing against an external dynamometer, the Power Tap provides a valid and reliable measure of power output while cycling, within and between units.

Although there is a strong relationship between heart rate and power output during graded exercise in the laboratory, we observed a significant dissociation between heart rate and the real time pattern of power output in the field. As a result, heart rate cannot be used to predict the average power output, energy expenditure, or distribution of power output during competitive road cycling events. Because the heart rate response can be affected by more than just the power output, heart rate may still be indicative of the overall cardiovascular demands, but should not be thought of as synonymous with the metabolic or physical demands placed on skeletal muscle, especially in non-steady state events. Thus, previous studies that have used field-based measures of heart rate to describe the demands of competitive road cycling should be interpreted with caution.

The Power Tap and SRM power meters are sufficiently precise to distinguish the affects of body position and tire inflation pressure on measures of aerodynamic and rolling characteristics, giving drag area and rolling coefficient values that compare well with values reported in the literature on both relative and absolute scales. Compared to other techniques for assessing aerodynamic drag and rolling resistance, this technique is accessible, relatively easy to control, and the most specific technique for a given individual and their equipment for road cycling.
Because of the important performance consequences associated with changes in aerodynamic and rolling resistance this protocol is an important technique for better profiling individual cyclists and in conjunction with physiological measures should help coaches, athletes and scientists to better predict road cycling performance.

To predict cycling performance in the field a cyclist’s ability to produce power must be considered relative to the forces that resist forward motion. Accordingly, level time trial performance is best predicted by normalizing the actual level power output to a true representation of aerodynamic resistance. Similarly, uphill time trial performance is best predicted by normalizing the actual uphill power output to body or total mass. Though power at VO₂ peak or LT are not perfect predictors of field power, if power cannot be measured in the field, these variables when normalized to aerodynamic drag on the level or mass uphill, are still better predictors of field performance compared to field power alone. Moreover, despite the fact that physiological variables are commonly thought of as the most important determinant of performance, we found that alone, measures of aerodynamic resistance were better related to level performance than VO₂ peak, LT, or economy. Finally, neither economy nor rolling resistance improve the prediction of uphill or level time trial performance.
Appendix

Human Research Review Project Description for the Metabolic Validation of the Power Tap

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Project Title:

Validation of the VO 2000 Metabolic Measurement Unit

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Rationale:

The physical stress or dose associated with rehabilitation, therapy, exercise, training, and competition is normally inferred from an individual's acute psycho/physiological (e.g., perceived exertion, heart rate) response to the activity or exercise and not through direct measurements of the stress itself. In addition, the assessment of an individual's chronic adaptive response to an exercise or training program is often determined by measuring changes in an individual's maximal aerobic capacity and mechanical efficiency or economy. Most individuals do not have access to the expensive and often inaccessible laboratory equipment required to do such an evaluation. Consequently, clear relationships between an individuals exercise and or training program and the various physiological adaptations or performance outcomes that result have remained unclear.

Recently, a number of advances in technology have made it possible to measure both the acute physical stress (e.g., power output) and physiological strain (e.g., oxygen consumption) associated with most forms of exercise and activity while in the field. In addition, the enhanced portability of indirect calorimetry units used to measure oxygen consumption or energy expenditure (e.g., KB1-C, Aerosport Inc.), cycle ergometers, (e.g., CompuTrainer, RacerMate Inc.), and hand held computers now allow measurements normally limited to the laboratory to be accessed by athletes at anytime in the field. Unfortunately, the reliability and validity of these devices and analytical techniques has yet to be determined. Because or intent is to use these devices or similar technology during a longitudinal study scheduled for the year 2000, our current purpose is to determine the reliability and validity of this equipment during field and laboratory studies this Fall, beginning (September 1, 1999).
Methodology

Phase one of this project will begin September 1, 1999 and continue through to September 1, 2000. The purpose of this first phase is to assess the reliability and validity of the KB1-C portable metabolic measurement system, the Power Tap power meter, the SRM power meter, and the CompuTrainer cycle ergometer. In addition, it is our intent to assess the logistical demands and practicality of using this equipment over the course of an entire competitive season. Consequently, this project will be distinguished by work in both the field and laboratory.

In the field, 3 athletes from the Celestial Seasonings Pro Women's Cycling Team will be equipped with both an SRM power meter and a Power Tap power meter. These athletes will be used to collect and record daily data about their competitive and training environment. Approximately every 4 weeks a standard graded exercise stress test will be performed on these athletes using the CompuTrainer and KB1-C.

In the laboratory, 10 additional cyclists recruited from the greater Boulder area will be used to assess the reliability and validity of the KB1-C and CompuTrainer. In addition, the reliability and validity of the Power Tap, the SRM, and the CompuTrainer will be assessed using an external dynamometer or power generator, which is attached to the bicycle and is independent of the subject.

Subjects & Recruitment Methods

The athletes studied in the field will be recruited primarily from the Celestial Seasonings Women's Cycling Team. The team, which is based in Boulder, Colorado, currently consists of 8 members, ages 19 to 35. As part of a sponsorship program with Tune Corporation, the Celestial Seasonings cycling Team has already committed to using the Power Tap this season. We have solicited the team for 3 volunteers to share the data that they collect with the Power Tap during the summer and to add the SRM to their existing monitoring platform. At present, we have limited our request to 3 athletes because we have access to only 3 SRM power meters. If more than 3 athletes from the team choose to volunteer, these additional athletes will only be providing data with the Power Tap. Beyond the Celestial Seasonings Cycling Team, we have posted information about our current study and subject needs with Tune Corporation and the manufacturers of the SRM power meter.

In addition to our field evaluations, ten volunteer United States Cycling Federation (USCF) category II or better cyclists age 18 to 35 will be used to assess the reliability and validity of the KB1-C portable metabolic unit and CompuTrainer. These athletes will be recruited from the greater Boulder area through flyers posted at local bicycle races, bike shops, and fitness gyms.
Field Monitoring:

Prior to any testing or data collection the subjects will be asked to fill out a medical questionnaire, to review the informed consent, and will be given a detailed description of all testing and measurement procedures. This medical questionnaire will be used to screen athletes for medical contraindication to exercise stress testing as detailed by the American College of Sports Medicine in their Guidelines For Exercise Stress Testing and Prescription, 1995. During the review of the informed consent, the athlete will not only be asked to read the informed consent but also be given a verbal explanation of the measurements taken and the attendant risks, discomforts and benefits. As well, the athlete will be assured that all the information gathered would remain completely confidential and any questions the athlete may have will be answered.

Ideally, the field athletes participating in this study will be equipped with both an SRM and Power Tap power meter. However, athletes equipped with only an SRM or Power Tap will not be excluded form the study. Each day, heart rate, power, work, cadence, time, and distance data collected by these devices will be downloaded to a laptop computer or Palm Pilot. The Palm Pilot and laptop computers used will each contain an electronic training journal. The journal will allow each athlete to easily record descriptive data such as weight, hours of sleep, hours of training, type of training or racing, environmental conditions, caloric intake, and mood-state. All of the above data will be e-mailed to the University of Colorado at Boulder via the Internet and stored on a central database at the University. This database will be used to begin the development of an artificial neural network that will be used to model the dose-response relationship in this population. Data gathered with the Power Tap and the SRM will be compared with one another to assess the overall stability and durability of both monitoring platforms. The specific competitive events that will be evaluated with the Power Tap and SRM include the following:

1) First Union Liberty Classic  
2) Hewlett Packard International Women's Challenge  
3) US National Championships  
4) Red Zinger Classic  
5) Tour De Toona

At present, there are no known risks of using portable power meters during training or competition. Although, bicycle racing is an inherently dangerous sport, the athletes participating in this study have assumed their own liability for participating in the sport of cycling as licensed members of the United States Cycling Federation. While our field research will not be presenting any physical risk beyond these athlete's normal activity, it is possible that these athletes may perceive access of their personal training records by their competitors as threatening. As such, it is our intent to code the identity of any athlete participating in our study and to hold our data with strict confidence and security.
The benefits of systematically collecting and storing information about an athlete’s training and competitive environment are innumerable. Foremost, the feedback about the physical demands of training and competition will provide these athletes and their coaches with valuable information that will help them to better evaluate and plan their training. For example, the ability to evaluate an athlete’s physiological response to a known quantity of physical work may help these athletes avoid over-training. Also, by participating in our study, we will be able to help these athletes manage and analyze the data they collect with techniques that might not otherwise be available to them.

In addition to data collection with the power meters and training journals, we also plan to perform a graded exercise test on each of the athletes in the field approximately every 4 weeks. Each exercise test will be performed on the athlete’s personal bicycle attached to a ComputTrainer cycle ergometer that will be used to regulate the resistance during the test. After a 15-minute warm-up at 60 watts, the first stage, lasting 4 minutes, will begin at a workload of 60 watts. After the first stage, the workload will be increased by 40 watts. Every 4 minutes thereafter, the workload will be increased by 20 watts until the athlete reaches a rating of perceived exertion (RPE) on the Borg scale of 15. Once an RPE of 15 is reached the workload will be decreased to 60 watts and the athlete will be given 10 minutes of active recovery. The first segment constitutes the submaximal portion of the exercise test and will last approximately 20 to 28 minutes. After 10 minutes of active recovery, the maximal portion of the exercise test will begin at the second to last workload completed during the submaximal exercise stress test. Each stage of the maximal exercise stress test will last 1 minute with an increase of 20 watts each minute. The maximal exercise stress test will end when the athlete reaches volitional fatigue and requests to end the test. The athlete will be encouraged to continue pedaling while the workload is decreased to 60 watts and monitored during a 10 minute cool down. During both the submaximal and maximal exercise test, energy expenditure or oxygen consumption, heart rate, and perceived exertion will be measured each minute.

Oxygen consumption and energy expenditure will be measured using open circuit indirect calorimetry with the KB1-C metabolic unit. In order to measure both submaximal and maximal oxygen consumption, the subjects will be asked to place a rubber mouth piece similar to a snorkel in their mouth and have their nose pinched closed with a plastic (pneumotach) and hosing that leads to a gas analyzer. Because the subject will not be able to speak while oxygen consumption is measured, subjects will be continually asked about their well being with yes and no questions and asked to respond with appropriate hand signals.

There are no known risks of oxygen consumption measurements using open circuit indirect calorimetry. The most common discomfort is temporary dryness of the throat. Subjects can expect to benefit by measurement of oxygen consumption because it can give the athlete a direct measurement of caloric expenditure, which can be correlated to workload or heart rate. This information can be used to assess the caloric needs of the athlete. Also, economy or the oxygen cost of a submaximal workload can be calculated and is a strong indicator along with maximal oxygen consumption of endurance performance. Maximal oxygen consumption is an
indicator of an individual’s maximal aerobic capacity and can be useful to the athlete in assessing his or her aerobic fitness.

The potential risks of graded exercise testing in this population are exceptionally low with a 1 in 20,000 risk of death. Some potential risks and discomforts may include nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmia’s, and light-headedness. Any symptom that threatens the safety or well being of the subject will result in immediate termination of the test. After the test the subject may also experience some nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmia’s, light-headedness, as well as some muscle soreness 1 to 2 days following the test. Because fainting may result from the sudden cessation of work, subjects will be instructed to cool down and continue light pedaling after test termination. The subjects will be instructed to cool down and continue light pedaling after test termination. The subjects will be continually monitored during their cool down and assisted by trained staff. Should any emergency arise, emergency equipment and staff will be on hand to implement the appropriate emergency protocol. All tests will be overseen by an American College of Sports Medicine certified exercise test technologist trained in basic life support.

Despite the potential risks and discomforts, there are numerous benefits of graded exercise tests. These tests provide a unique opportunity for subjects to explore their maximal work capacity under a controlled environment. Feedback regarding the athlete’s strengths, weaknesses and current fitness from the physiological measurements made will then be relayed to the athlete. The athlete may use this information to enhance their individual training methods.

Laboratory Monitoring:

As the first aspect of the laboratory testing, the reliability and validity of the Power Tap power meter, the SRM power meter, and the CompuTrainer portable electronically braked cycle ergometer will be checked against an external dynonameter or power generator. Specifically, the CompuTrainer mounted to a bicycle equipped with an SRM and Power Tap will be mechanically checked with an Vacumed external dynonameter (Ventura, California) over a range of cadences (50 to 155 rpm at 15 rpm intervals) and workloads (50 to 1000 watts at 50 watt intervals). These same tests will be performed on our standard Quinton cycle ergometer to also assure that all of the equipment used during testing is properly calibrated.

During the month of July, ten volunteer United States Cycling Federation (USCF) category II or better cyclists age 18 to 35, recruited from the greater Boulder area, will be used to assess the reliability and validity of the KB1-C portable metabolic unit and the Computrainer during graded exercise tests. The exercise test protocol used will be exactly the same as the graded exercise tests that will be used with the field athletes. The athletes studied in the laboratory, however, will perform this test 4 times, each test separated by 1 day. The type of indirect calorimetry device used to measure oxygen consumption and the ergometer used to control workload will distinguish each testing period (Table 1). Oxygen consumption will be measured using either the KB1-C or a computer assisted metabolic cart equipped that will serve
as our standard. The CompuTrainer portable ergometer fitted with the athlete’s personal bicycle or the Quinton ergometer (standard) will be used to control workload. When the ComputTrainer is used, the Power Tap will also be used to measure power output.

**Table 1:** The four testing combinations that will be randomly employed for each subject.

<table>
<thead>
<tr>
<th>Indirect Calorimetry Devices</th>
<th>Ergometers:</th>
</tr>
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<tbody>
<tr>
<td>KB1-C</td>
<td></td>
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<tr>
<td>Control (Mass Spec)</td>
<td></td>
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<tr>
<td>CompuTrainer</td>
<td>1) KB1-C/CompuTrainer 2) Mass Spec/CompuTrainer</td>
</tr>
<tr>
<td>Control (Quinton)</td>
<td>3) KB1-C/Quinton 4) Mass Spec/Quinton</td>
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</table>

Like the field athletes, each athlete studied in the laboratory will be asked to fill out a medical questionnaire, to review the informed consent, and will be given a detailed description of all testing and measurement procedures prior to testing. During the review of the informed consent, the athlete will not only be asked to read the informed consent but also be given a verbal explanation of the measurements taken and the attendant risks, discomforts and benefits. As well, the athlete will be assured that all the information gathered would remain completely confidential and any questions the athlete may have will be answered. The same risks and benefits of graded exercise testing in our field athletes also apply to the athletes studied in the laboratory.

All the measurements taken as well as the protocols used for this study have proven effective and safe through many years of research at both the Human Performance Laboratory at the University of Colorado at Boulder. The investigators have read and understood the General Guidelines on the Rights and Welfare of Human Subjects (Senate Document 79-012), and agree to comply with all clauses to the best of their ability. In addition to consideration described in this project description, the investigators fully intend to conduct all procedures with the subject’s best interest in mind in order to ensure their safety and comfort.
Informed Consent: Metabolic Validation of Power Tap

Department of Kinesiology and Applied Physiology
University of Colorado at Boulder
Campus Box 354

STATEMENT OF INFORMED CONSENT

Project Title: Pilot Work relating to the proposed study “A Direct and Longitudinal Assessment of the Dose-Response Relationship in Elite Cyclists”

Investigators:

Allen C. Lim, M.S. (Doctoral candidate)  Phone 588-2144
Douglas C. Ziewacz, B.A. (Master’s candidate)  Phone 402-0379
William C. Byrnes, Ph.D. (Advisor)  Phone 492-5301

Procedures:

You are volunteering to participate in 4 submaximal and maximal exercise tests as part of a pilot study to verify the reliability and validity of the Power Tap power meter. During these exercise tests, your energy expenditure or oxygen consumption, ventilation rate, heart rate, carbon dioxide production, rating of perceived exertion, and workload will be measured.

Prior to participation, you will be asked to complete a medical history questionnaire. If you exhibit no contraindications to strenuous exercise as outlined by the American College of Sports Medicine; you will be scheduled for 4 submaximal and maximal exercise tests which will be performed over a 3-week period. During each of your 4 visits to the laboratory, the following protocol will be used during the submaximal and maximal exercise tests. Before each test, you will perform a 15 to 30-minute warm-up at a light workload. The submaximal stress test will begin at a light workload for a period of 4 minutes at a pedaling cadence of 90 r.p.m. After this initial load the workload will be increased slightly. Every 4 minutes thereafter, the workload will be increased slightly every 4 minutes. The submaximal exercise test will end when you reach a rating of perceived exertion (RPE) of 15 on the Borg scale (RPE 15 = Very Hard). At the end of the submaximal test you will be given a 10-minute rest, after which you will begin the maximal stress test. The maximal stress test will begin at the second to last achieved workload during the submaximal stress test. The resistance will be increased slightly every 1 minute until you feel you cannot continue and volitionally end the test. The test will also end if you can no longer maintain a cadence of 90 r.p.m. or if the test supervisor chooses to end the test. You may stop at any time. Two of the exercise tests will be performed on your personal bicycle using the CompuTrainer cycle ergometer while 2 exercise
tests will be performed using the standard electronically braked bicycle (Lode Excaliber) fitted with your pedals and adjusted to your dimensions.

For the measurement of energy expenditure or oxygen consumption, you will be fitted with a mouthpiece connected to the Perkins-Elmer Mass Spectrometer. Measurements of oxygen uptake, carbon dioxide output, and ventilation rate will be made with both the KB1-C and the Perkins-Elmer Mass Spectrometer computer assisted indirect calorimetry system.

**Risks and Discomforts:** The potential risks for participating in this study are those associated with intense exercise. In the endurance-trained population selected for this study, these risks are minimal but include the possibility of irregular heart rhythms, abnormal blood pressure, and heart attack. Emergency support equipment and trained staff will be available to deal with any unusual situation, should it arise. The discomforts of fatigue, shortness of breath, nausea, light headedness, dry mouth and skin irritation from the electrodes are possible. A test will be terminated should any symptom put your safety in jeopardy.

**Potential Benefits:** You will receive an interpretation of the test results from the investigators. This interpretation will provide information concerning the functional status of your cardiorespiratory system. The knowledge gained from this study will assist the investigators in evaluating the Power Tap power meter and in developing cycle ergometer test procedures to be used with the longitudinal assessment of elite cyclists.

**Inquiries:** Any questions, which you may have about the tests, are welcomed and encouraged. If you have any doubts or concerns, please ask for further explanation. Questions concerning your rights as a subject can be directed to the Executive Secretary, Human Research Committee, Campus Box 26, Regent 308, at the Graduate School of the University of Colorado. Upon request, you may receive a copy of the institution’s general assurance from the Human Research Committee, University of Colorado, Boulder, CO. 80309 (Phone: 303-492-7401). Questions concerning the study may be directed to Doug Ziewacz (303-402-0379 or Dr. William C. Byrnes (303-492-5301), Kinesiology Department, Campus Box 354, University of Colorado, Boulder, CO 80309-0354.

**Confidentiality:** The information obtained during this study will be treated as privileged and confidential. It will not be released or revealed to anyone except upon your written request. The intent of these pilot studies is to practice with instrumentation to be used in the field and to improve testing procedures but data may also be used for publication. Information obtained and used for statistical analyses and scientific purposes will only be used with your right to privacy maintained. Some of the data may be recorded on the Human Performance Laboratory’s computerized database to be used exclusively for this study. Access to the data can only be obtained by written permission from the laboratory. Subjects will be referred to as a numerical figure on all reports and publications related to this data and the data in the computer’s database.
**Freedom of Consent:** Your participation in this project is voluntary, and you are free to deny consent. You are free to discontinue participation at any time. The investigators have read and understood the General Guidelines on the Rights and Welfare of Human Subjects (Senate Document 79-012), and agree to comply with all clauses to the best of their ability. In addition to consideration described in this document, the investigators fully intend to conduct all procedures regarding your best interest, and to inure your safety and comfort.

I acknowledge that I have read this form in its entirety, or it has been read to me, and that I understand the procedures in which I will be engaged. I, thereby, consent to participation in this project.

Signature _____________________________________  Date ____________

Witness _______________________________________  Date ____________
Human Research Project Description for Field Studies on Heart Rate vs. Power Output

Department of Kinesiology and Applied Physiology
Campus Box 354
Boulder, CO 80309-0354
303-588-2144

University of Colorado at Boulder Human Research Committee

• Request for Regular Institutional Review/Approval

Project Title:

The relationship between stress and strain based measures of exercise intensity during training and competition in professional cyclists.

Investigators:

Name: Title:
Allen C. Lim Doctoral Candidate / Co-Principal Investigator
William C. Byrnes Student Advisor / Co-Principal Investigator
Benjamin M. Turner Master’s Candidate / Graduate Research Assistant
Lindsey Sweeney Undergraduate Honors Candidate

I. Background and Purpose:

It is well accepted that the physiological adaptations induced by a given training program are specific to the program used and to the individual challenged. Known respectively as “specificity” and “individuality”, these concepts suggest that a sound training program should closely mimic the demands of competition in an amount or dose that optimizes an individual’s personal response. Unfortunately, technological limitations have made it difficult to accurately assess the demands of competition and training. Consequently, training programs and laboratory tests designed to enhance and assess athletic performance may not be specific to the requirements of competition. In addition, these monitoring limitations have made the relationship between an athlete’s adaptive response and their training and competitive program difficult to define.

Normally, the type, duration, frequency, and intensity of exercise characterize the demands or “load” induced by an athlete’s training and competitive program. While most of these variables are simple to monitor, exercise intensity, which lacks a singular description, is more complex. For example, measures of exercise intensity can be classified as either “stress” or “strain” based. In this context, stress represents the severity of the physical stimulus challenging an athlete (e.g., power output, workload, speed) while strain represents the ensuing psychological or physiological response (e.g., perceived exertion, heart rate, energy expenditure).

Although exercise intensity is most accurately described by using both stress and strain based measures, most athletes evaluate exercise intensity only by utilizing
strain-based measures like heart rate response or perceived exertion. This is because, until recently, the technology to accurately quantify stress measures like power output during exercise in real world settings has not existed. As a result, heart rate response and perceived exertion have become the most commonly used measure of exercise intensity during training and competition. Though there is a tight relationship between heart rate response and power output in the laboratory, this relationship is easily dissociated by different environmental, psychological, and physiological factors. In fact, recent pilot data from our laboratory show that in competitive road cycling, heart rate response is not a reliable inference of an athlete’s power output. Moreover, changes in an athlete’s fitness inherently change the relationship between stress and strain. For instance, as an athlete gains fitness a given stress produces less strain.

Ultimately, the majority of training programs and laboratory tests designed to enhance and assess athletic performance are based on strain based measures of intensity. Because of the dissociation that can occur between stress and strain, it is likely that these programs and tests are not specific to the demands of competition. In addition, without a quantifiable measure of stress as a reference point for potential changes in strain, evaluating an athlete’s adaptation to a particular training program is nearly impossible. Finally, without actually measuring the stress associated with competitive events and training the true demands of these events remains unknown.

Recently, the development of portable power meters or dynonameters located in the crank arm or rear hub of a bicycle have become available. These devices are capable of recording variables like, power output, speed, and torque, making it possible to easily measure stress during training and competition. Given the inherent limitations of strain-based measures of exercise intensity, the use of this equipment presents new possibilities in the realm of exercise science and human performance.

II. Purpose:

The purpose of this study is to investigate the relationship between stress and strain based measures of exercise intensity during training and competition in a group of professional cyclists utilizing portable power meters. Specifically, we intend to compare the power output profiles generated by professional cyclists in real-world settings and compare them to heart rate response and perceived exertion. In addition, we intend to compare these real world profiles against standard measures of performance in the laboratory.

III. Subjects:

The subjects recruited for our study will be female (n=10) and male (n=10) professional cyclists between the ages of 18-35 years. Specifically, our subjects will be recruited from teams that currently use portable power meters as a training tool. These teams include the Elita Professional Cycling Team, the 7-Up/Colorado Cyclist Professional Cycling Team, the US Postal Service Professional Cycling Team, the Canadian Olympic Long Team, and the US Olympic Long Team. For events monitored in the field, our subject pool will range between 2 to 20 athletes. All subjects monitored in the field will be monitored in the laboratory,
Limiting this study to elite cyclists already utilizing portable power meters has a number of benefits. First, the use of professional or elite cyclists helps to ensure that the individual’s participating in this study are highly trained and accustomed to the physical demands of training and competition. This will help to ensure our goal of assessing the relationship between stress and strain in real competitive events without placing demands on our subjects that would exceed what would be considered their normal routine. Moreover, documenting the extreme training loads and physiological capacity of these subjects is itself scientifically interesting. Finally, portable power meters are presently limited primarily to professional cyclists.

IV. Methods:

A. Pre-Screening and Orientation:

Prior to the study each subject will undergo an orientation where both field and laboratory procedures will be explained. During this orientation, subjects will be asked to fill out a medical questionnaire and to review the informed consent. The medical questionnaire will be used to screen subjects for medical contraindications to exercise stress testing as detailed by the American College of Sports Medicine in their Guidelines for Exercise Stress Testing and Prescription. During the review of the informed consent, the subjects will not only be asked to read the informed consent but will also be given a verbal explanation of the measurements taken and the attendant risks, discomforts and benefits. In addition, the subjects will be assured that all the information gathered will remain completely confidential. Any questions the subjects may have will be answered.

B. Field Monitoring:

At a number of select races and during training athletes will be asked to share information gathered with their portable power meters. At present these events include the Altoona Stage Race (July 31 to August 5, 2001) and the Saturn Cycling Challenge (August 11, 2001). The variables measured by the portable power meters will include power output (watts), pedal cadence (revolutions per minute), torque (Newton-meters), speed (mph), exercise duration, distance (miles), and heart rate. This information will be stored on an on-board computer that can be downloaded to a standard personal computer after each training session. This information can then be e-mailed to the investigators.

A short training diary will also be e-mailed to investigators throughout the study. The variables assessed will include duration of sleep, mood state, fatigue rating, muscle soreness, health rating, weight, weather conditions, fluid and dietary intake, and a brief description of the training or competitive session. This information will be recorded after each training and competitive session.

For those athletes volunteering to gather data at stage races (3 or more days of continuous racing) an additional measurement will be added. An hour before each race, athletes will be asked to warm up on a standard bicycle trainer for 5 minutes at
150 watts. During this warm-up the athletes heart rate will also be monitored as will their rating of perceived exertion.

Risks and Discomforts associated with Field Monitoring:

The measurements made in the field pose no risks to the subjects above those normally encountered by them during training and competition. The primary concern for subjects is confidentiality of data. Confidentiality will be maintained by coding each subject’s data and by maintaining data in a password-protected database. Data will only be accessible to investigators and will not be shared with anyone without written consent from the subject. Because the responsibility of field monitoring is entirely up to the subjects, each subject will be encouraged to remain diligent throughout the study. However, the investigators realize that the sharing of data by subjects is entirely voluntary. While the attrition rate may be high, subjects are free to withdraw from the study at anytime. Any action or behaviors by anyone associated with this study that either physically or emotional harms a subject will be reported and dealt with immediately.

C. Laboratory Monitoring:

Each subject will be evaluated in the Human Performance Laboratory in the Department of Kinesiology and Applied Physiology at the University of Colorado at Boulder. The evaluation will consist of a graded exercise stress test, body composition assessment, and three maximal efforts at 90%, 100%, and 120% of their peak power output. Subjects will be scheduled for one laboratory visit consisting of two days of testing within 2 weeks of their first field monitoring session. All the measurements taken as well as the protocols used in the laboratory have been proven effective and safe through many years of research at both the Human Performance Laboratory at the University of Colorado at Boulder and at facilities like the U.S. Olympic Training Center in Colorado Springs, Colorado.

i. Graded Exercise Stress Test:

Measurements:

- Blood Lactate via finger pricks.
- Oxygen Consumption via indirect calorimetry.
- Heart rate using a Polar heart rate monitor.
- Rating of perceived exertion using the Borg scale.

Exercise Protocol:

The graded exercise stress test will occur on the subject’s personal bicycle equipped with their power meter and attached to a CompuTrainer® electronically braked bicycle trainer. The test will be composed of a submaximal and maximal phase. The submaximal test will begin at a workload of 100 watts for men and 50
watts for women. Workload will increase by 30 watts every 4 minutes until subjects reach a workload that they feel is sustainable but still very hard (Rating of perceived exertion equal to 15 on the Borg 6 to 20 scale). Subjects will then be allowed a 10-minute passive or active recovery phase before proceeding to the maximal stress test. The maximal stress test will begin at the penultimate stage of the sub-maximal stress test. Workload will be increased by 30 watts every minute. Subjects will be encouraged to go as long as possible. The test will end when subjects can no longer continue and chooses to stop. Immediately after the maximal test ends, the subjects will be encouraged to continue pedaling while the workload is decreased to 50 watts.

*Risks and Discomforts associated with the Exercise Protocol:*

The potential risks of graded exercise stress testing in this population are exceptionally low. The primary risks and discomforts may include nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmias, and light-headedness. These are the same risks and discomforts faced by our subjects during training and competition. Unlike, most training and competitive situations, however, the subjects will be carefully monitored throughout the test. Any symptom that threatens the safety or well being of the subject will result in immediate termination of the test. After the test the subject may also experience some nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmias, light-headedness, as well as some muscle soreness 1 to 2 days following the test. Because fainting may result from the sudden cessation of work, subjects will be instructed to cool down and continue light pedaling after test termination. Trained staff will continually monitor the subjects during testing and their cool down. Should any emergency arise, emergency equipment and staff will be on hand to implement the appropriate emergency protocol. All tests will be overseen by an American College of Sports Medicine certified exercise test technologist trained in basic life support.

*Benefits of the Exercise Protocol:*

Despite the potential risks and discomforts, there are numerous benefits of a graded exercise stress test. These tests provide a unique opportunity for subjects to explore their maximal work capacity under a controlled environment. Feedback regarding the subject’s strengths, weaknesses and current fitness from the physiological measurements made will then be relayed to the subject. In addition, subjects will be able to evaluate data collected in training against physiological reference points. Ultimately, the subjects may use this information to enhance their individual training methods.

*Measurement of Blood Lactate:*

Capillary blood samples will be obtained over the last 30 seconds of each workload during the sub-maximal test and 2 minutes after maximal exercise for blood lactate assessment. A fingertip sterilized with rubbing alcohol will be mechanically pricked with a spring-loaded tool called an autolet device containing a sterile needle.
Approximately 50 μl of whole blood will be drawn into a heparinized capillary tube from blood drops on the pricked finger. Exactly 25 μl of whole blood will be aspirated from the capillary tube using a sterile pipette and injected into a sterile 500 μl microcentrifuge tube filled with a 50 μl buffer solution, lysing agent (Octylphenoxethanol), and glycolytic inhibitor (NaF anhydrous). The blood-buffer solution will then be vortexed and analyzed with a YSI 2300 Stat Plus lactate analyzer. Investigators sampling and handling blood will wear protective latex medical gloves and protective eyewear during the test. Subjects will have their finger pricked at the end of each stage for a total of 3 to 8 finger pricks. Between each prick, subjects will be given a sterile piece of gauze treated with an antibacterial gel and instructed to place direct pressure on the pricked finger. All the supplies used during exercise for blood analysis and sampling as well as all analyzed and excess blood samples will be disposed of in biohazard bags sealed in cardboard boxes. Contaminated boxes will be picked up weekly by a certified medical waste agency.

**Risks and Discomforts associated with Blood Lactate Measurement:**

The risks of blood draws from finger prick are minimal. A small percentage of subjects may experience light-headedness and fainting when exposed to blood. Individuals known to experience this phenomenon will be screened out of the study prior to testing. To minimize potential problems, however, all subjects will be asked to look away from the pricked finger during testing. If this does not alleviate problems and a subject cannot complete the test due to the discomfort or problems associated with the finger prick, the subject will be excused from the study. Finally, exposure to blood may present a risk to the investigators conducting the tests. All investigators handling or coming into contact with blood will wear protective lab coats, gloves, and eye wear throughout the test.

**Benefits of Blood Lactate Measurement:**

The major benefit of blood lactate analysis is the assessment of a subject’s lactate threshold. We are specifically interested in identifying each subject’s lactate threshold because it is a strong predictor of endurance performance. Identifying where a subject’s lactate threshold occurs relative to heart rate and workload may help subjects in planning their training and assessing their fitness.

**Measurement of Oxygen Consumption:**

Energy expenditure or oxygen consumption will be measured using open circuit indirect calorimetry. In order to measure both sub-maximal and maximal oxygen consumption, the subjects will be asked to place a rubber mouth piece similar to a snorkel in their mouth and have their nose pinched closed with a plastic nose plug during exercise. This mouthpiece will be attached to a respiratory valve connected to hosing that leads to a gas analyzer and a ventilation meter. Because the subject will not be able to speak while oxygen consumption is measured, each minute, subjects
will be asked to point at a rating of perceived exertion scale (Borg) in order to evaluate their well being.

*Risks and Discomforts associated with Oxygen Consumption Measurements:*

There are no known risks of oxygen consumption measurements using open circuit indirect calorimetry. The most common discomfort is temporary dryness of the throat.

*Benefits of Oxygen Consumption Measurements:*

Subjects can expect to benefit by measurement of oxygen consumption because it can give the subject a direct measurement of caloric expenditure. This information can be used to assess the caloric needs of the subject and to assess the energy requirements of various power outputs. Also, economy or the oxygen consumed at a given sub-maximal workload is a strong indicator along with maximal oxygen consumption and lactate threshold of endurance performance. Maximal oxygen consumption is an indicator of an individual's maximal aerobic capacity and can be useful to the subject in assessing his or her aerobic fitness.

**ii. Body Composition Assessment:**

Percent body-fat, fat-free mass, total and regional adipose tissue mass, and total bone mineral density will be determined using a whole-body dual energy x-ray absorptiometry scan (DXA, Model DPX-IQ Lunar Corp., Madison, WI).

There is a small amount of radiation exposure (0.05 mRem) associated with the DXA which is less than 1/20 of a typical chest x-ray. The more radiation one receives over the course of one's life, the more risk of having cancerous tumors or of inducing changes in genes. The changes in genes possibly could cause abnormalities or disease in a subject's offspring. The radiation in this study is not expected to greatly increase these risks, but the exact increase in such risks is unclear. **Women who are or could be pregnant should receive no unnecessary radiation and will not be allowed to participate in this study.**

**iii. Maximal Power Output vs. Time:**

*Exercise Protocol:*

On the second day of testing subjects will be asked back to the laboratory to assess the duration that they can hold 90%, 100%, and 120% of the power output associated with their VO$_2$ max or peak power. After a 15-minute warm-up at 50-150 watts, the power output will be set at 120% of their peak power output. They will be asked to maintain this power output for as long as possible. Depending upon their fitness level, the effort may last anywhere from 1 to 3 minutes. After this first effort, they will be given a 30-minute recovery period before they are asked to perform at 100% of their peak power output. This effort may last anywhere from 2 to 6 minutes.
Following another 30-minute recovery period they will be asked to perform the final effort at 90% of their peak power output. This effort may last anywhere from 4 to 10 minutes.

During each effort, oxygen consumption, heart rate, and perceived exertion will be measured each minute in the same manner as in the graded exercise stress test. Blood lactate will be measured via finger pricks two minutes following each maximal effort for a total of 3 finger pricks.

The potential risks and discomforts associated with these maximal efforts are the same as those associated with the graded exercise stress test. Likewise, the benefits of these efforts are similar to those associated with the results gained from the graded exercise stress test. It is our hope, however, that the results of these performance measures will enhance our ability to predict and evaluate fitness in ways that are distinct from the graded exercise stress test. If this is true, then the results of these tests may enhance our ability to predict performance over the more traditional measures performed during the graded exercise stress test.
Informed Consent for Field Studies Examining Heart Rate vs. Power Output

Human Performance Laboratory
Department of Kinesiology and Applied Physiology
University of Colorado at Boulder
UCB 354
Boulder, CO 80309-0354

Statement of Informed Consent

Project Title:

The relationship between stress and strain based measures of exercise intensity during training and competition in professional cyclists: The Altoona Stage Race.

Investigators:

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<th>Name</th>
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<tr>
<td>Allen C. Lim</td>
<td>Co-Investigator / Doctoral Candidate</td>
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<td>William C. Byrnes</td>
<td>Co-Investigator / Associate Professor</td>
<td>303-492-5301</td>
</tr>
<tr>
<td>Benjamin M. Turner</td>
<td>Graduate Research Assistant</td>
<td>303-735-</td>
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<tr>
<td>Lindsey Sweeney</td>
<td>Undergraduate Honors Candidate</td>
<td>303-735-</td>
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Background, Significance, and Purpose:

You are volunteering to participate in a research study examining the demands of competition at the Altoona Stage Race in Altoona, Pennsylvania from July 31 to August 5, 2001. The principle objective of the study is to document the demands associated with competition using a rear hub (Power Tap(r)) or crank based (SRM(r)) power meter and heart rate monitor as the primary measures of exercise intensity.

In endurance sports like cycling exercise intensity has been primarily measured indirectly by evaluating heart rate response and perceived exertion. Though there is a strong relationship between heart rate response and power output in the laboratory, this relationship can be dissociated by a number of different factors during competition. In fact, recent pilot data from our laboratory show that in competitive cycling, heart rate response is not always a reliable inference of an athlete's power output. As a result, previous assessments of the demands associated with competition that are based on heart rate monitoring, may not be entirely accurate. Until the advent of the portable power meter, however, a direct measure of the demands associated with competition and training in cycling has not been possible. With the recent availability of both hub and crank based power meters, it is our intent to monitor your
power output, heart rate response, and perceived exertion during competition at the Altoona Stage Race.
In addition to evaluating your heart rate and power profiles from competition, we are also interested in how these field measures compare with the results of both traditional and non-traditional laboratory performance tests. These traditional tests include an assessment of your maximal oxygen consumption (VO2 max), lactate threshold, and economy. In addition to these tests, we are also interested in assessing your performance by quantifying the time to fatigue at 90%, 100%, and 120% of the power output associated with your VO2 max.
Ultimately, our goal is to better understand the real world demands associated with training and competition in the sport of cycling in an attempt to better predict and optimize performance. By accurately quantifying the demands associated with competition and the relationship between these demands and performance in both the laboratory and the field, we will have made a critical first step towards this goal.

Project Overview:

I) Screening / Orientation:

During the screening you will be asked to fill out a training and medical questionnaire and review the informed consent. At this time, a review of all testing procedures, equipment and specific instructions will be given. If your medical history shows no potential risks to exercise stress testing and you consent to participate you will be scheduled for two sequential days of laboratory testing. These laboratory sessions will occur either a week before or a week following the Altoona Stage Race.

II) Overview of Field Monitoring:

During field monitoring you will be primarily responsible for using a rear hub or crank based power meter during the entire stage race and returning your power meter's computer to researchers who will download the data to a central database after each day of racing. In addition to using the power meter, you will be asked to fill out a simple training diary that will be provided to you.

III) Overview of Laboratory Testing:

You will be evaluated in the Human Performance Laboratory at the University of Colorado at Boulder within a week prior or week after the Altoona Stage Race. The testing sessions will be spaced over two days. The first day of testing will require a time commitment of one and a half hours. During this first day of testing a graded exercise stress test to exhaustion will be performed and your oxygen consumption, heart rate, blood lactate, and rating of perceived exertion will be measured. The second day of testing will require a time commitment of two and a half hours. During this testing session the relationship between time and maximal power will be
assessed. Essentially, you will be asked to ride at 80%, 100%, and 120% of the power output associated with your maximal oxygen consumption until exhaustion. Each effort will last between one to ten minutes depending upon your fitness and will be separated by a thirty-minute rest period. During each effort, your oxygen consumption, blood lactate, and rating of perceived exertion will be measured. All exercise sessions will be performed on a Lode Excaliber bicycle ergometer fitted with your own saddle and pedals and adjusted to the measurements of your personal bicycle.

In addition to your exercise tests, your body composition (% lean muscle mass, % fat mass, and bone density) will be assessed at the University of Colorado at Boulder on the first day of testing. This will require an additional thirty-minute time commitment.

IV) Project Feedback:

Results of laboratory tests and data analysis will be returned to you within a month of the Altoona Stage Race.

Description of Methods: Attendant Risks, Discomforts and Benefits.

I) Field Monitoring:

You will be asked to share information gathered with your power meter during competition at the Altoona Stage Race. In addition, you will be asked to fill out a short training diary each day (See attached questionnaire). The training diary asks you to give a short (1 to 5 sentence) description of the event and asks you to rate on a scale of one to ten your perceived exertion, your level of perceived fatigue, and your level of perceived fitness.

All information gathered during the Altoona Stage Race will be held in the strictest confidence. All databases used in this study will be password protected and the identity of subjects will be coded.

II) The Graded Exercise Stress Test:

Exercise Protocol:

After a 15-minute warm-up at 50 watts, the first stage, lasting four minutes, will begin at a workload of 50 watts for females and 100 watts for males. Every three minutes the workload will be increased by 25 watts until you reach an intensity that you feel is "very hard." After this point, the workload will be decreased to 50 watts and you will be allowed 10 minutes of active recovery. This first segment constitutes the submaximal portion of the exercise stress test and will last approximately 16 to 25 minutes. After the 10-minute recovery, the maximal exercise stress test will begin at the second to last workload completed during the submaximal exercise stress test. Each stage of the maximal exercise stress test will last 1 minute with an increase of
25 watts each minute. The maximal exercise stress test will end when you are completely exhausted or request to stop. Immediately after the test you will be continually monitored and asked to complete a 10-15 minute cool down consisting of light pedaling at 0 to 50 watts.

Risks and Discomforts associated with a Graded Exercise Stress Test:

The potential risks of a graded exercise stress test include the possibility of abnormal blood pressure, abnormal heart rhythms and fainting due to the sudden cessation of work. Discomforts may include nausea, shortness of breath, fatigue, light-headedness and muscle soreness 1 to 2 days after the test. Any symptom that threatens your safety will result in immediate termination of the test. You may choose, however, to terminate the test at any point in time.

Benefits of a Graded Exercise Stress Test:

Despite the potential risks and discomforts, there are numerous benefits of submaximal /maximal exercise stress tests. These tests provide a unique opportunity for you to explore your maximal work capacity under a controlled environment. As well, the physiological variables monitored may provide invaluable feedback regarding your strengths, weaknesses and current fitness. This information provides will also provide us with physiological references that will be compared with data collected during your training and competition. Potential findings may help you to better understand how your performance is influenced by training and competition.

Measurement of Oxygen Consumption:

In order to measure submaximal and maximal oxygen consumption you will be asked to place a rubber mouthpiece similar to a snorkel in your mouth during exercise. This mouthpiece will be attached to a respiratory valve connected to hosing that leads to a gas analyzer and a ventilation meter. During this procedure, your nose will be sealed with a nose plug. Because you will not be able to talk during this process due to interference by the mouthpiece the attending staff and researchers will communicate with you through yes and no questions and with a chart that lists a gradation of exertion levels (rating of perceived exertion scale). The collection of accurate data is dependent upon secure placement of the mouthpiece and nose plug during the entire duration of exercise. However, if at any time you feel constricted or need to communicate essential information concerning your welfare please feel free to remove the apparatus.

Risks and Discomforts Associated with the Measurement of Oxygen Consumption:

There are no known risks of oxygen consumption measurement. However, the mouthpiece can often cause temporary dryness of the throat.

Benefits of Oxygen Consumption Measurement:
The benefits of oxygen consumption measurement include the ability for us to calculate the oxygen cost of submaximal work giving you an indication of your economy. Economy along with lactate threshold and your maximal oxygen consumption can be a strong indicator of performance and help you understand some of your physiological strengths and weaknesses. Also, oxygen consumption is directly linked to caloric expenditure and thus the number of calories burned for any given workload can be calculated and correlated to heart rate and power output. This information may be useful in determining the metabolic cost or energy expenditure of your training.

Measurement of Heart Rate:

Heart rate will be measured with a Polar Vantage XL heart rate monitor that consists of an electronic sensor which is strapped to your chest during exercise and which transmits heart rate data to a receiver.

Variables such as oxygen consumption, power output and lactate correlate quite well with heart rate. In the field, heart rate will be used as our physiological measure of exercise intensity. The relationship between this variable and power output in both the field and the laboratory may give us important insight into your physiological status.

Measurement of Blood Lactate:

Lactate threshold will be analyzed through blood samples taken through finger pricks at the end of each 3-minute stage during the submaximal exercise stress test. Approximately 2-3 drops of blood will be taken per stage. The total number of finger pricks will be dependent upon the total number of submaximal stages you are able to complete. Normally, the total number of finger pricks range from a minimum of 3 to a maximum of 8 pricks.

Risks Associated with the Measurement of Blood Lactate:

The risks of blood draws through finger pricks are minimal. A small percentage of individuals experience light-headedness and fainting when exposed to blood. Some momentary pain will be felt while the finger is being pricked. If you have experienced fainting at the sight of blood in the past, please inform the investigators.

Benefits of Blood Lactate Measurement:

The benefits of blood sampling include the assessment of lactate threshold that can be used by you in determining specific training intensities and zones that correlate to particular heart rates and workloads.

III. Body Composition Assessment:
On the day of your graded exercise stress test your percent body-fat, fat-free mass, total and regional adipose tissue mass, and total bone mineral density will be determined using a whole-body dual energy x-ray absorptiometry scan (DXA, Model DPX-IQ Lunar Corp., Madison, WI).

There is a small amount of radiation exposure (0.05 mRem) associated with the DXA which is less than 1/20 of a typical chest x-ray. The more radiation one receives over the course of one's life, the more risk of having cancerous tumors or of inducing changes in genes. The changes in genes possibly could cause abnormalities or disease in a subject's offspring. The radiation in this study is not expected to greatly increase these risks, but the exact increase in such risks is unclear. Women who are or could be pregnant should receive no unnecessary radiation and will not be allowed to participate in this study.

IV. Maximal Power Output vs. Time:

Exercise Protocol:

On the second day of testing you will be asked back to the laboratory to assess the duration that you can hold 90%, 100%, and 120% of the power output associated with your maximal oxygen consumption (VO2 max). After a 15-minute warm-up at 50-150 watts, the power output will be set at 120% of the power output associated with your VO2 max. You will be asked to maintain this power output for as long as possible. Depending upon your fitness level, the effort may last anywhere from 1 to 3 minutes. After this first effort, you will be given a 30-minute recovery period before you are asked to perform at 100% of your maximal power output. This effort may last anywhere from 2 to 6 minutes. Following another 30-minute recovery period you will be asked to perform the final effort at 90% of your maximal power output. This effort may last anywhere from 4 to 10 minutes.

During each effort, oxygen consumption, heart rate, perceived exertion, and blood lactate will be measured each minute in the same manner as your graded exercise stress test.

The potential risks and discomforts associated with these maximal efforts are the same as those associated with your graded exercise stress test. Likewise, the benefits of these efforts are similar to those associated with the results gained from your graded exercise stress test. It is our hope, however, that the results of these performance measures will enhance our ability to predict and evaluate your fitness in ways that are distinct from the graded exercise stress test. If this is true, then the results of these tests may enhance our ability to predict performance over the more traditional measures performed during the graded exercise stress test.

Inquires:

Any questions about this project and the measurements involved are welcomed and encouraged. If you have any doubts or concerns please ask for further explanations. Questions regarding your rights as a subject can be directed to the Human Research
Executive Secretary at the Graduate School of the University of Colorado Boulder (303-492-7401). Upon request, you may also receive a copy of the institution’s general assurance from the Human Research Executive Secretary. Questions may be directed to any of the listed investigators.

Confidentiality:

The information and measurements obtained during all phases of this project will be treated as privileged and confidential. No information will be released or revealed to any person other than those directly involved as investigators in this research without your written consent. However, the data may be used for statistical analysis and scientific presentation with your right to privacy retained.

Freedom to Consent:

Your participation in this project is completely voluntary and you are free to deny consent. If you decide to participate, you may rescind this decision during any stage of the project.

The investigators have read and understood the General Guidelines on the Rights and Welfare of Human Subjects (Senate Document 79-012), and agree to comply with all clauses to the best of their ability. In addition to considerations described in this document, the investigators fully intend to conduct all procedures in a manner that ensures your safety and comfort.

I have read this form in its entirety, or it has been read to me, and I understand the procedures in which I will be engaged. I hereby consent to participate in this project.

Signature __________________________________________ Date __________

Witness __________________________________________ Date __________
Human Research Project Description for Power Monitoring in the Field

Department of Kinesiology and Applied Physiology
Campus Box 354
Boulder, CO 80309-0354
303-588-2144

University of Colorado at Boulder Human Research Committee

- Request for Regular Institutional Review/Approval

Project Title:

The relationship between stress and strain based measures of exercise intensity during training and competition in professional cyclists.

Investigators:

Name: 
- Allen C. Lim
- William C. Byrnes
- Benjamin M. Turner
- Lindsey Sweeney

Title:
- Doctoral Candidate / Co-Principal Investigator
- Student Advisor / Co-Principal Investigator
- Master's Candidate / Graduate Research Assistant
- Undergraduate Honors Candidate

I. Background and Purpose:

It is well accepted that the physiological adaptations induced by a given training program are specific to the program used and to the individual challenged. Known respectively as "specificity" and "individuality", these concepts suggest that a sound training program should closely mimic the demands of competition in an amount or dose that optimizes an individual's personal response. Unfortunately, technological limitations have made it difficult to accurately assess the demands of competition and training. Consequently, training programs and laboratory tests designed to enhance and assess athletic performance may not be specific to the requirements of competition. In addition, these monitoring limitations have made the relationship between an athlete's adaptive response and their training and competitive program difficult to define.

Normally, the type, duration, frequency, and intensity of exercise characterize the demands or "load" induced by an athlete's training and competitive program. While most of these variables are simple to monitor, exercise intensity, which lacks a singular description, is more complex. For example, measures of exercise intensity can be classified as either "stress" or "strain" based. In this context, stress represents the severity of the physical stimulus challenging an athlete (e.g., power output, workload, speed) while strain represents the ensuing psychological or physiological response (e.g., perceived exertion, heart rate, energy expenditure).

Although exercise intensity is most accurately described by using both stress and strain based measures, most athletes evaluate exercise intensity only by utilizing strain-based measures like heart rate response or perceived exertion. This is because,
until recently, the technology to accurately quantify stress measures like power output during exercise in real world settings has not existed. As a result, heart rate response and perceived exertion have become the most commonly used measure of exercise intensity during training and competition. Though there is a tight relationship between heart rate response and power output in the laboratory, this relationship is easily dissociated by different environmental, psychological, and physiological factors. In fact, recent pilot data from our laboratory show that in competitive road cycling, heart rate response is not a reliable inference of an athlete’s power output. Moreover, changes in an athlete’s fitness inherently change the relationship between stress and strain. For instance, as an athlete gains fitness a given stress produces less strain. Ultimately, the majority of training programs and laboratory tests designed to enhance and assess athletic performance are based on strain based measures of intensity. Because of the dissociation that can occur between stress and strain, it is likely that these programs and tests are not specific to the demands of competition. In addition, without a quantifiable measure of stress as a reference point for potential changes in strain, evaluating an athlete’s adaptation to a particular training program is nearly impossible. Finally, without actually measuring the stress associated with competitive events and training the true demands of these events remains unknown. Recently, the development of portable power meters or dynonameters located in the crank arm or rear hub of a bicycle have become available. These devices are capable of recording variables like, power output, speed, and torque, making it possible to easily measure stress during training and competition. Given the inherent limitations of strain-based measures of exercise intensity, the use of this equipment presents new possibilities in the realm of exercise science and human performance.

II. Purpose:

The purpose of this study is to investigate the relationship between stress and strain based measures of exercise intensity during training and competition in a group of professional cyclists utilizing portable power meters. Specifically, we intend to compare the power output profiles generated by professional cyclists in real-world settings and compare them to heart rate response and perceived exertion. In addition, we intend to compare these real world profiles against standard measures of performance in the laboratory.

III. Subjects:

The subjects recruited for our study will be female (n=10) and male (n=10) professional cyclists between the ages of 18-35 years. Specifically, our subjects will be recruited from teams that currently use portable power meters as a training tool. These teams include the Elita Professional Cycling Team, the 7-Up/Colorado Cyclist Professional Cycling Team, the US Postal Service Professional Cycling Team, the Canadian Olympic Long Team, and the US Olympic Long Team. For events monitored in the field, our subject pool will range between 2 to 20 athletes. All subjects monitored in the field will be monitored in the laboratory,
Limiting this study to elite cyclists already utilizing portable power meters has a number of benefits. First, the use of professional or elite cyclists helps to ensure that the individual’s participating in this study are highly trained and accustomed to the physical demands of training and competition. This will help to ensure our goal of assessing the relationship between stress and strain in real competitive events without placing demands on our subjects that would exceed what would be considered their normal routine. Moreover, documenting the extreme training loads and physiological capacity of these subjects is itself scientifically interesting. Finally, portable power meters are presently limited primarily to professional cyclists.

IV. Methods:

A. Pre-Screening and Orientation:

Prior to the study each subject will undergo an orientation where both field and laboratory procedures will be explained. During this orientation, subjects will be asked to fill out a medical questionnaire and to review the informed consent. The medical questionnaire will be used to screen subjects for medical contraindications to exercise stress testing as detailed by the American College of Sports Medicine in their Guidelines for Exercise Stress Testing and Prescription. During the review of the informed consent, the subjects will not only be asked to read the informed consent but will also be given a verbal explanation of the measurements taken and the attendant risks, discomforts and benefits. In addition, the subjects will be assured that all the information gathered will remain completely confidential. Any questions the subjects may have will be answered.

B. Field Monitoring:

At a number of select races and during training athletes will be asked to share information gathered with their portable power meters. At present these events include the Tour de France (July 1-23), the Red Zinger (July 15th), the Tour de Toona (August 1-6), the Women’s Tour de France (August 6-20), the Montreal Grand Prix (August 16-20), and the Olympic Games (September 26, 30). The variables measured by the portable power meters will include power output (watts), pedal cadence (revolutions per minute), torque (Newton-meters), speed (mph), exercise duration, distance (miles), and heart rate. This information will be stored on an on-board computer that can be downloaded to a standard personal computer after each training session. This information can then be e-mailed to the investigators.

A short training diary will also be e-mailed to investigators throughout the study. The variables assessed will include duration of sleep, mood state, fatigue rating, muscle soreness, health rating, weight, weather conditions, fluid and dietary intake, and a brief description of the training or competitive session. This information will be recorded after each training and competitive session.

For those athletes volunteering to gather data at stage races (3 or more days of continuous racing) an additional measurement will be added. An hour before each race, athletes will be asked to warm up on a standard bicycle trainer for 5 minutes at
150 watts. During this warm-up the athletes heart rate will also be monitored as will their rating of perceived exertion.

Risks and Discomforts associated with Field Monitoring:

The measurements made in the field pose no risks to the subjects above those normally encountered by them during training and competition. The primary concern for subjects is confidentiality of data. Confidentiality will be maintained by coding each subject’s data and by maintaining data in a password-protected database. Data will only be accessible to investigators and will not be shared with anyone without written consent from the subject. Because the responsibility of field monitoring is entirely up to the subjects, each subject will be encouraged to remain diligent throughout the study. However, the investigators realize that the sharing of data by subjects is entirely voluntary. While the attrition rate may be high, subjects are free to withdraw from the study at anytime. Any action or behaviors by anyone associated with this study that either physically or emotional harms a subject will be reported and dealt with immediately.

C. Laboratory Monitoring:

Each subject will be evaluated in the Human Performance Laboratory in the Department of Kinesiology and Applied Physiology at the University of Colorado at Boulder. The evaluation will consist of a graded exercise stress test and body composition assessment. Subjects will be scheduled for one laboratory visit within 2 weeks of their first field monitoring session. All the measurements taken as well as the protocols used in the laboratory have been proven effective and safe through many years of research at both the Human Performance Laboratory at the University of Colorado at Boulder and at facilities like the U.S. Olympic Training Center in Colorado Springs, Colorado.

i. Graded Exercise Stress Test:

Measurements:

- Blood Lactate via finger pricks.
- Oxygen Consumption via indirect calorimetry.
- Heart rate using a Polar heart rate monitor.
- Rating of perceived exertion using the Borg scale.

Exercise Protocol:

The graded exercise stress test will occur on the subject’s personal bicycle equipped with their power meter and attached to a CompuTrainer® electronically braked bicycle trainer. The test will be composed of a submaximal and maximal phase. The submaximal test will begin at a workload of 100 watts for men and 50 watts for women. Workload will increase by 30 watts every 4 minutes until subjects
reach a workload that they feel is sustainable but still very hard (Rating of perceived exertion equal to 15 on the Borg 6 to 20 scale). Subjects will then be allowed a 10-minute passive or active recovery phase before proceeding to the maximal stress test. The maximal stress test will begin at the penultimate stage of the sub-maximal stress test. Workload will be increased by 30 watts every minute. Subjects will be encouraged to go as long as possible. The test will end when subjects can no longer continue and chooses to stop. Immediately after the maximal test ends, the subjects will be encouraged to continue pedaling while the workload is decreased to 50 watts.

*Risks and Discomforts associated with the Exercise Protocol:*

The potential risks of graded exercise stress testing in this population are exceptionally low. The primary risks and discomforts may include nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmias, and light-headedness. These are the same risks and discomforts faced by our subjects during training and competition. Unlike, most training and competitive situations, however, the subjects will be carefully monitored throughout the test. Any symptom that threatens the safety or well being of the subject will result in immediate termination of the test. After the test the subject may also experience some nausea, shortness of breath, fatigue, abnormal blood pressure response, cardiac arrhythmias, light-headedness, as well as some muscle soreness 1 to 2 days following the test. Because fainting may result from the sudden cessation of work, subjects will be instructed to cool down and continue light pedaling after test termination. Trained staff will continually monitor the subjects during testing and their cool down. Should any emergency arise, emergency equipment and staff will be on hand to implement the appropriate emergency protocol. All tests will be overseen by an American College of Sports Medicine certified exercise test technologist trained in basic life support.

*Benefits of the Exercise Protocol:*

Despite the potential risks and discomforts, there are numerous benefits of a graded exercise stress test. These tests provide a unique opportunity for subjects to explore their maximal work capacity under a controlled environment. Feedback regarding the subject’s strengths, weaknesses and current fitness from the physiological measurements made will then be relayed to the subject. In addition, subjects will be able to evaluate data collected in training against physiological reference points. Ultimately, the subjects may use this information to enhance their individual training methods.

*Measurement of Blood Lactate:*

Capillary blood samples will be obtained over the last 30 seconds of each workload during the sub-maximal test and 2 minutes after maximal exercise for blood lactate assessment. A fingertip sterilized with rubbing alcohol will be mechanically pricked with a spring-loaded tool called an autolet device containing a sterile needle. Approximately 50 µl of whole blood will be drawn into a heparinized capillary tube
from blood drops on the pricked finger. Exactly 25 μl of whole blood will be aspirated from the capillary tube using a sterile pipette and injected into a sterile 500 μl microcentrifuge tube filled with a 50 μl buffer solution, lysing agent (Octylphenoxethanol), and glycolytic inhibitor (NaF anhydrous). The blood-buffer solution will then be vortexed and analyzed with a YSI 2300 Stat Plus lactate analyzer. Investigators sampling and handling blood will wear protective latex medical gloves and protective eyewear during the test. Subjects will have their finger pricked at the end of each stage for a total of 5 to 8 finger pricks. Between each prick, subjects will be given a sterile piece of gauze treated with an antibacterial gel and instructed to place direct pressure on the pricked finger. All the supplies used during exercise for blood analysis and sampling as well as all analyzed and excess blood samples will be disposed of in biohazard bags sealed in cardboard boxes. Contaminated boxes will be picked up weekly by a certified medical waste agency.

*Risks and Discomforts associated with Blood Lactate Measurement:*

The risks of blood draws from finger prick are minimal. A small percentage of subjects may experience light-headedness and fainting when exposed to blood. Individuals known to experience this phenomenon will be screened out of the study prior to testing. To minimize potential problems, however, all subjects will be asked to look away from the pricked finger during testing. If this does not alleviate problems and a subject cannot complete the test due to the discomfort or problems associated with the finger prick, the subject will be excused from the study. Finally, exposure to blood may present a risk to the investigators conducting the tests. All investigators handling or coming into contact with blood will wear protective lab coats, gloves, and eye wear throughout the test.

*Benefits of Blood Lactate Measurement:*

The major benefit of blood lactate analysis is the assessment of a subject’s lactate threshold. We are specifically interested in identifying each subject’s lactate threshold because it is a strong predictor of endurance performance. Identifying where a subject’s lactate threshold occurs relative to heart rate and workload may help subjects in planning their training and assessing their fitness.

*Measurement of Oxygen Consumption:*

Energy expenditure or oxygen consumption will be measured using open circuit indirect calorimetry. In order to measure both sub-maximal and maximal oxygen consumption, the subjects will be asked to place a rubber mouth piece similar to a snorkel in their mouth and have their nose pinched closed with a plastic nose plug during exercise. This mouthpiece will be attached to a respiratory valve connected to hosing that leads to a gas analyzer and a ventilation meter. Because the subject will not be able to speak while oxygen consumption is measured, each minute, subjects will be asked to point at a rating of perceived exertion scale (Borg) in order to evaluate their well being.
Risks and Discomforts associated with Oxygen Consumption Measurements:

There are no known risks of oxygen consumption measurements using open circuit indirect calorimetry. The most common discomfort is temporary dryness of the throat.

Benefits of Oxygen Consumption Measurements:

Subjects can expect to benefit by measurement of oxygen consumption because it can give the subject a direct measurement of caloric expenditure. This information can be used to assess the caloric needs of the subject and to assess the energy requirements of various power outputs. Also, economy or the oxygen consumed at a given sub-maximal workload is a strong indicator along with maximal oxygen consumption and lactate threshold of endurance performance. Maximal oxygen consumption is an indicator of an individual’s maximal aerobic capacity and can be useful to the subject in assessing his or her aerobic fitness.

ii. Body Composition Assessment:

Body composition will be evaluated using dual energy x-ray absorptiometry (DEXA). Lying in a supine position an x-ray equivalent to the radiation exposure of 1/20th of a chest x-ray. There are no known risks or discomforts associated with this measurement. Subjects will benefit from the knowledge of their body composition which includes bone density, body fat, lean muscle mass.
Informed Consent for Field Monitoring of Power

University of Colorado at Boulder
Department of Kinesiology and Applied Physiology
Campus Box 354
Boulder, CO 80309-0354

Statement of Informed Consent

Project Title:

The relationship between stress and strain based measures of exercise intensity during training and competition in professional cyclists.

Investigators:

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<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Phone Number</th>
</tr>
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<tbody>
<tr>
<td>Allen C. Lim</td>
<td>Co-Investigator / Doctoral Candidate</td>
<td>303-588-2144</td>
</tr>
<tr>
<td>William C. Byrnes</td>
<td>Co-Investigator / Associate Professor</td>
<td>303-492-5301</td>
</tr>
<tr>
<td>Benjamin M. Turner</td>
<td>Graduate Research Assistant</td>
<td>303-245-1182</td>
</tr>
<tr>
<td>Lara Kroespch</td>
<td>Undergraduate Honors Candidate</td>
<td>303-440-8993</td>
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</tbody>
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Background, Significance, and Purpose:

You are volunteering to participate in a research study examining the demands of training and competition. The principle objective of the study is to document your daily training loads as well as the demands of a select number of competitive events using a rear hub power meter and heart rate monitor as the primary measures of exercise intensity.

In the past, exercise intensity has been primarily measured by evaluating only heart rate response and perceived exertion. Though there is a tight relationship between heart rate response and power output in the laboratory, this relationship is easily dissociated by different environmental, psychological, and physiological factors. In fact, recent pilot data from our laboratory show that in competitive cycling, heart rate response is not a reliable inference of an athlete’s power output. Because of this dissociation between heart rate and power output, it is likely that training programs and laboratory tests designed to enhance and assess athletic performance in competitive cycling are not specific to the demands of competition.

Because power meters in competitive cycling have become readily available to professional and elite cyclists, we hope to study the relationship between power output and heart rate during both training and competition. In addition, we would like to evaluate how power and heart rate measures from training and competition compare with standard laboratory performance tests. Ultimately, our goal is to create training programs and laboratory tests that are more specific to the demands faced by competitive cyclists in real world settings.
Project Overview:

This project will begin upon your consent and terminate whenever you chose. Our goal, however, is to monitor as many days of training and racing as you consent to for the following year.

I) Screening / Orientation:

During the screening you will be asked to fill out a training and medical questionnaire and review the informed consent. At this time, a review of all testing procedures, equipment and specific instructions will be given. If your medical history shows no potential risks to exercise stress testing and you consent to participate you will be scheduled for your laboratory testing session. In addition a schedule will be generating listing the racing events that will be monitored.

II) Field Monitoring:

During field monitoring you will be primarily responsible for downloading daily training information from your power meter to your personal computer and filling out a training diary that will be provided to you. You will then be required to e-mail this information to the investigators at the University of Colorado at Boulder. In addition to the providing information on your daily training you will be asked to collect data using your power meter at a select number of races. These races will be up to your discretion. You will be encouraged to send us as many days of training and racing as possible. However, the decision to use your power meter and to provide us data is ultimately up to you.

III) Laboratory Testing Session (1.5 hours):

A laboratory performance test will be scheduled within a few weeks of participating for this study. During the testing session a graded exercise stress test to exhaustion will be performed and your oxygen consumption, heart rate, blood lactate, and rating of perceived exertion will be measured. All exercise will be performed on your personal bicycle fitted to a CompuTrainer® electronically braked bicycle trainer.

Immediately before your stress test, your body composition will also be assessed using a low energy x-ray scan.

Description of Methods: Attendant Risks, Discomforts and Benefits.

I) Field Monitoring:

At a number of select races and during training you will be asked to share information gathered with your power meter. You will do this by downloading your data to your personal computer and then e-mailing this information to Allen Lim at limh@ucsu.colorado.edu.
If you choose to share data from stage races, you will also be required to participate in a 5-minute warm-up approximately 1 hour prior to each race. The warm-up will be conducted on a bicycle trainer at 150 watts. This file will be in addition to your race data.

At a number of stage races research assistants will be available from the University of Colorado at Boulder to assist you in data collection and troubleshooting. At present, these events include the Red Zinger (July 15th), the Tour de Toona (August 1-6), and the Montreal Grand Prix (August 16-20). You will be informed if these events are changed or if events are added.

In addition to downloading and e-mailing information from your power meter you will also be asked to fill a short training diary each day (See attached questionnaire). This training diary will be provided to you either in electronic form or as a hard copy. Each week you will be asked to e-mail or mail this training diary to Allen Lim, Department of Kinesiology and Applied Physiology, Campus Box 354, Boulder, CO 80309—0354.

II) The Graded Exercise Stress Test:

Exercise Protocol:

After a 15-minute warm-up at 50 watts, the first stage, lasting four minutes, will begin at a workload of 50 watts for females and 100 watts for males. Every three minutes the workload will be increased by 30 watts until you reach an intensity that you feel is “very hard.” After this point, the workload will be decreased to 50 watts and you will be allowed 10 minutes of active recovery. This first segment constitutes the submaximal portion of the exercise stress test and will last approximately 16 to 25 minutes. After the 10-minute recovery, the maximal exercise stress test will begin at the second to last workload completed during the submaximal exercise stress test. Each stage of the maximal exercise stress test will last 1 minute with an increase of 30 watts each minute. The maximal exercise stress test will end when you are completely exhausted or request to stop. Immediately after the test you will be continually monitored and asked to complete a 10-15 minute cool down consisting of light pedaling at 0 to 50 watts.

Risks and Discomforts associated with a Graded Exercise Stress Test:

The potential risks of a graded exercise stress test include the possibility of abnormal blood pressure, abnormal heart rhythms and fainting due to the sudden cessation of work. Discomforts may include nausea, shortness of breath, fatigue, light-headedness and muscle soreness 1 to 2 days after the test. Any symptom that threatens your safety or well being will result in immediate termination of the test.

Benefits of a Graded Exercise Stress Test:

Despite the potential risks and discomforts, there are numerous benefits of submaximal /maximal exercise stress tests. These tests provide a unique opportunity
for you to explore your maximal work capacity under a controlled environment. As well, the physiological variables monitored may provide invaluable feedback regarding your strengths, weaknesses and current fitness.

**Measurement of Oxygen Consumption:**

In order to measure submaximal and maximal oxygen consumption you will be asked to place a rubber mouthpiece similar to a snorkel in your mouth during exercise. This mouthpiece will be attached to a respiratory valve connected to hosing that leads to a gas analyzer and a ventilation meter. During this procedure, your nose will be sealed with a nose plug. Because you will not be able to talk during this process due to interference by the mouthpiece the attending staff and researchers will communicate with you through yes and no questions and with a chart that lists a gradation of exertion levels (Borg or rating of perceived exertion scale). The collection of accurate data is dependent upon secure placement of the mouthpiece and nose plug during the entire duration of exercise. However, if at any time you feel constricted or need to communicate essential information concerning your welfare please feel free to remove the apparatus.

**Risks and Discomforts Associated with the Measurement of Oxygen Consumption:**

There are no known risks of oxygen consumption measurement. However, the mouthpiece can often cause temporary dryness of the throat.

**Benefits of Oxygen Consumption Measurement:**

The benefits of oxygen consumption measurement include the ability for us to calculate the oxygen cost of submaximal work giving you an indication of your economy. Economy along with lactate threshold and your maximal oxygen consumption can be a strong indicator of performance and help you understand some of your physiological strengths and weaknesses. Also, oxygen consumption is directly linked to caloric expenditure and thus the number of calories burned for any given workload can be calculated and correlated to heart rate. This information may be useful in determining the metabolic cost or energy expenditure of your training.

**Measurement of Heart Rate:**

Heart rate will be measured with a Polar Vantage XL heart rate monitor which consists of an electronic sensor which is strapped to your chest during exercise and which telemeters heart rate data to a receiver.

Variables such as oxygen consumption, power output and lactate correlate quite well with heart rate. Thus, heart rate can be used as an index for work and helping to fine tune training intensity.

**Measurement of Blood Lactate:**
Lactate threshold will be analyzed through blood samples taken through finger pricks at the end of each 3-minute stage during the submaximal exercise stress test. Approximately 2-3 drops of blood will be taken per stage.

*Risks Associated with the Measurement of Blood Lactate:*

The risks of blood draws through finger pricks are minimal. A small percentage of individuals experience light headedness and fainting when exposed to blood. Some momentary pain will be felt while the finger is being pricked. If you have experienced fainting at the sight of blood in the past, please inform the investigators.

*Benefits of Blood Lactate Measurement:*

The benefits of blood sampling include the assessment of lactate threshold that can be used by you in determining specific training intensities and zones that correlate to particular heart rates and workloads.

**III. Body Composition Assessment:**

Before your graded exercise stress test your bone density, lean muscle mass, and body fat will be evaluated using a low energy x-ray scan. The amount of radiation you will be exposed to during this scan is equivalent to the radiation exposed to individuals on a commercial airline flight from Denver to Los Angeles. During this scan you will be asked to wear a bathing suit and to remove all metallic jewelry and clothing. While there are no known risks of this form of body composition assessment, the major benefit will be to assure that your bone density is within normal limits.

Inquires:

Any questions about this project and the measurements involved are welcomed and encouraged. If you have any doubts or concerns please ask for further explanations. Questions regarding your rights as a subject can be directed to the Human Research Committee at the Graduate School of the University of Colorado Boulder. Upon request, you may also receive a copy of the institution’s general assurance from the Human Research Committee Secretary, University of Colorado Boulder, Boulder Colorado, 80309. Questions may be directed to any of the listed investigators.

Confidentiality:

The information and measurements obtained during all phases of this project will be treated as privileged and confidential. No information will be released or revealed to any person other than those directly involved as investigators in this
research without your written consent. However, the data may be used for statistical analysis and scientific presentation with your right to privacy retained.

**Freedom to Consent:**

Your participation in this project is completely voluntary and you are free to deny consent. If you decide to participate, you may rescind this decision during any stage of the project.

The investigators have read and understood the General Guidelines on the Rights and Welfare of Human Subjects (Senate Document 79-012), and agree to comply with all clauses to the best of their ability. In addition to considerations described in this document, the investigators fully intend to conduct all procedures with your best interest in mind in order to ensure your safety and comfort.

I have read this form in its entirety, or it has been read to me, and I understand the procedures in which I will be engaged. I hereby consent to participate in this project.

Signature_________________________________________ Date______________

Witness_________________________________________ Date______________
Human Research Project Description for Prediction of Uphill and Level Time Trial Performance

Request for Review

Project Title: Predicting road cycling performance using physiological and resistance to movement variables

PI: William Byrnes, PhD (303-492-5301, byrnes@spot.colorado.edu)
Co-PI: Allen Lim, MS (303-735-1358, limh@colorado.edu)

I. Purpose and Significance

Predicting and understanding athletic performance is often hampered by our ability to isolate and measure the appropriate factor or set of factors important to a given performance. This is especially true as the complexity of the event increases. Therefore, exercise scientists have emphasized less complex sports like distance running when studying athletic performance.

In distance running, there are three key physiological attributes determining performance in short (e.g., mile) to long events (e.g., marathon). They include an athlete’s ability to maximally consume oxygen ($\overline{VO}_2$ max or peak), the percentage of $\overline{VO}_2$ max at which the appearance of lactate in the blood exceeds its clearance from the blood (lactate threshold or LT), and the amount of oxygen required for a given running velocity (economy).

Because of the strong relationship between these physiological characteristics and performance in running, attempts have been made to predict cycling performance using these variables. In cycling, there is a strong relationship between these factors and the maximal power output an athlete can sustain for a given duration. Unlike running, however, the relationship between these variables and actual field performance during cycling is poor.

This discrepancy is not entirely surprising since cycling velocity is dependent on an athlete’s external power output and factors that resist forward motion. Historically, scientists have remained predominately focused on the physiological
basis of an athlete’s power output, assuming that the resistance faced by a moving cyclist is relatively constant. We have, however, documented differences in aerodynamic resistance amongst competitive cyclists as large as 35%, or the equivalent of a 10-minute time difference in a 40 km time trial at the same power output. Moreover, in the only study to measure the actual power output during a field time trial (16.1 km), Balmer et al., (2000) found no significant relationship between average power output and actual performance time ($r = 0.46, p > 0.05$), demonstrating the critical role played by resistance factors.

The total resistance ($R_{TOT}$) impeding the forward motion of a cyclist is greatly influenced by terrain and velocity with gravitational resistance the primary form of resistance during uphill cycling and aerodynamic resistance contributing largely to level cycling at constant speeds. During uphill cycling performance is best predicted by knowing an athlete’s power to weight ratio. To accurately predict performance on flat terrain, however, power output must be normalized to some measure of a cyclist’s aerodynamic character. Though several investigators, using wind tunnel data, downhill coasting tests, and anthropometric measures, have proposed means by which to assess this aerodynamic character these techniques have yet to be adopted on a broad scale and may not reflect the true aerodynamic profile of a given individual in the field.

In the last year, we developed a field protocol to assess the true aerodynamic and rolling resistance of a cyclist moving over level terrain by assessing the relationship between velocity and power output for an individual cyclist using a cycle mounted power meter located at the hub or crank. Our protocol is sensitive enough to detect changes in aerodynamic resistance caused by changes in body position independent of changes in rolling resistance caused by changes in tire pressure. Because of this sensitivity, we believe that we have a technique that can accurately measure the aerodynamic profile of a specific cyclist.

If our protocol for assessing an individual’s resistance to movement profile is indeed accurate, then measuring a cyclist’s resistance to movement profile with this technique in combination with physiologically based determinants of performance should significantly improve our ability to predict performance over a physiological assessment alone or a physiological assessment in conjunction with existing estimates of a cyclist’s resistance to movement profile. Accordingly the specific aims of our proposed studying include the following:

1) Assess the physiological profile ($VO_2$ max, lactate threshold, economy, and body composition) of a group of highly experienced competitive cyclists using standard laboratory protocols.

2) Assess the aerodynamic and rolling resistance profile of these cyclists by measuring power and velocity with a crank or hub based power meter while cycling over level terrain.

3) Estimate aerodynamic resistance by quantifying the frontal surface area of an individual cyclist by analyzing digital photos of that cyclist in competitive positions.
4) Measure performance during level and uphill individual time trials conducted in the field using standard measures of time as well as power measured using cycle mounted power meters.

5) Assess the relationship between level and uphill individual time trial performance in the field (dependent variable) with the physiological and resistance to movement profiles assessed in the laboratory (independent variables).

II. Methodology

A. Study Overview

After subjects are recruited they will be scheduled for an orientation meeting where the risks, benefits, and requirements for the study will be detailed in an oral presentation and in written form via the informed consent. Those athletes who volunteer for the study will then be scheduled for a pre-study meeting to become more familiar with the methods and equipment used for the study. The study will officially begin with a one to two week familiarity period where the training and dietary pattern of the subjects will be monitored. After this period, on two consecutive Saturday or Sunday mornings subjects will perform one uphill and one level field time trial. Within two weeks of their first time trial they will perform a graded exercise stress test in the laboratory and a body composition assessment via dual energy x-ray absorptiometry. After their final time trial, subjects will have their aerodynamic and rolling resistance profile measured during an outdoor field test and through digital photographs taken in the laboratory. Figure 1, diagrams the specific time commitment, window, and organizational structure for each phase.
Figure 1. The specific events planned for this study and their time frame.

B. Subject Population

Male cyclists from the greater Denver-Boulder community between the ages of eighteen and thirty-five years who are licensed to race with the United States Cycling Federation (USCF) at the category one, two, or professional level will be recruited. This specific category of cyclist is considered to be highly experienced in competitive cycling. Consequently, the efforts required during the graded exercise stress test, field time trials, and resistant to movement protocol should be very familiar to this population and should not pose a risk greater than they routinely experience in their normal training and racing. Thirty subjects will be admitted to this study with the goal of twenty completing the study.

A list of potential subjects will be solicited through the USCF public directory. From this directory and through bicycle shops, cycling teams, and cycling races, individual subjects will be recruited through a one-page flyer (Appendix A) disseminated through approved group e-mailings and physical posts. To assure that athletes are not coerced, no subjects will be recruited through their team management, coaches, or superiors. To assure that all athletes meet the skill level required for this study and to assure that all potential athletes completely understand the risk and benefits associated with this study, all subjects who are interested in participating will be required to attend a one-hour orientation meeting before being included in the study.

All subjects will be unpaid volunteers. Their primary incentive for participating in this study will be to better understand how their physiological and resistance to movement profile effects their personal performance. As competitive athletes, it is our hope that this information will be highly appealing and provide the personal and intrinsic motivation to volunteer for this study.

Women will not be included in this study at present because we are not confident that we can recruit enough USCF category 1, 2, or professional female cyclists from this area to achieve statistical power. Also, there is evidence that within a monthly menstrual cycle performance can be affected in female endurance athletes due to hormonal fluctuations. With critical performance measures spanning up to 3 weeks it would be difficult to isolate the impact of these hormonal changes.

C. Procedures

Familiarity Period

One to two weeks preceding the first time trial, subjects will be given detailed maps of the time trial courses and asked to familiarize themselves with the courses and the power meter they will use in the study. Subjects who have never ridden the
courses before will be asked to pre-ride each course at least twice. Those who are familiar with the courses will be asked to pre-ride each course at least once.

The power meters used in this study will include commercially available rear hub or crank based power meters that record power, torque, velocity, cadence, and heart rate. Data collected by the power meters will be stored to an onboard computer where information can be recalled or downloaded at a later time. The power meters used in this study have been used previously by our laboratory in competitive settings and are comparable to standard racing cranks and hubs.

During this period subjects will be asked to fill out a daily training diary (Appendix E) to document their training status leading into their first time trial. This training diary will also be used through their last time trial or laboratory GXT to ensure that their training status leading into performance measures is consistent. The two days preceding their first time trial and on the day of their first time trial, subjects will also fill out a dietary recall sheet (Appendix F). Subjects will be asked to mimic the diet and training routine preceding the first time trial before their laboratory GXT and their second time trial.

Our intent during this period is to ensure that each subject is completely comfortable with the equipment and time trial courses used for this study. Not only will this help to decrease a potential learning effect, it will also help to assure that the time trials performed by these subjects will not put them at a level of risk that is any greater than their normal training and racing routine.

**Field Time Trials (Uphill and Level):**

The uphill individual time trial course selected will begin at the intersection of 20th street and Baseline road in Boulder, Colorado and will proceed east up Baseline road to the top of Flagstaff road at an elevation of 7,851 feet (Distance = 7 miles, rise = 2,394 feet). The expected time on this course for the recruited population will range from 40 to 60 minutes.

This particular course has been selected for a number of reasons. First, it is a course that is extremely familiar to the competitive cyclists in this area. Anecdotally, elite and professional cyclists who live the Boulder community commonly use this route to assess their climbing fitness. Thus, we feel it is a course that our subjects will be highly familiar with and able to safely climb and descend. In addition, this particular stretch of road contains no stop signs or traffic lights and will allow the athletes to give a continuous and unobstructed effort. The steep grade of the road will allow us to isolate the role of gravitational resistance on performance. Finally, the presence of a large parking lot at the bottom of the climb and wide shoulders at the top of this particular climb provide a natural staging and finishing area that is out of the way of road traffic.

Within a week of completing the uphill time trial, subjects will be asked to complete a 34 km level time trial. The level time trial course selected will begin in Hygiene, Colorado just outside of Boulder at the corner of Hygiene road and 75th. Going east on Hygiene road subjects will make a right turn at Airport Road and proceed south to Nelson road. At Nelson road they will make another right turn and head west back to 75th Street where they will turn right heading north back to the start.
at Hygiene and 75th. The total length of one lap is 11.3 km. The subjects will complete 3 laps of this course to complete 34 km. The expected finishing time for our population will range from 45 minutes to 60 minutes.

This particular course was selected for a number of reasons. First and foremost, this particular course contains a wide and unobstructed shoulder at each intersection that gives a moving cyclist the right of way at each right hand turn. This will allow our subjects to give a continuous and unobstructed effort that is clear of potential traffic conflicts. In addition, this particular course does not rise or drop more than 100 feet over any 5 km stretch making it extremely flat, thereby allowing us to isolate the role of aerodynamic resistance on performance. Finally, the roads listed are popular training routes for competitive and recreational cyclists in the area and should be highly familiar to our population.

Subjects will perform one uphill time trial and one level time trial on two consecutive Saturday or Sunday mornings. No more than 10 subjects will be asked to perform a time trial on a given day to prevent any traffic problems. Each subject will be separated by a minimum of 2 minutes and asked to give an all out effort over the entire course. All subjects will be reminded to observe state and city traffic laws and to ride along the road shoulder out of the way of motor vehicle traffic. Subjects will be asked to prepare for this time trial exactly like they would a normal race and to follow all the safety precautions they would take while training or racing. These precautions include wearing an ANSI approved helmet, riding defensively, and maintaining a sense of control and safety throughout the test. All research assistants monitoring the time trial are trained in basic life support and first aid and will be carrying cell phones with them in case emergency services are needed.

A minimum of one research assistant will attend to subjects at the start of each course to record the start time of each subject. Another research assistant will attend to subjects at the finish to record the finishing time of each subject. A third research assistant will be located at the half way point of the course to help attend to any emergency situation.

**Graded Exercise Stress Test (GXT)**

Within two weeks of their first time trial, subjects will be asked to perform a GXT at the Applied Exercise Science Laboratory located in the East Campus Administrative Research Center. The GXT will be used to assess physiological attributes important to time trial performance including VO₂ max, the lactate threshold, economy. In addition, the GXT will be used to describe additional physiological responses to exercise including heart rate, perceived exertion, and oxyhemoglobin saturation. Although subjects will only be exercising for 20 to 40 minutes we will ask them for a time commitment of 1.5-hours to allow for adequate set-up and recovery.

Subjects will be asked to arrive at the laboratory 2.5 hours to 3 hours post-prandial and to prepare for the GXT as if they were preparing for a typical race, bringing with them their standard racing bicycle and equipment. Upon arrival at the laboratory, subjects will be re-oriented to the procedures, risks, and benefits of the GXT. Upon giving a verbal acknowledgement that they understand the procedures,
risks, and benefits, the subjects will be weighed and prepped with an 8 lead electrocardiogram (precordial, augmented, V2, and V5 leads).

The GXT will be performed on the subject’s personal bicycle mounted to an electronically braked bicycle trainer that will be used to adjust the workload. Power output will be measured directly with the crank or hub based power meter used during the time trial events. After a 10-minute warm-up at 100 watts, the GXT will begin at a workload of 150 watts, with the workload increasing by 30 watts every 4 minutes until volitional fatigue. At volitional fatigue workload will be immediately decreased to 50 watts and the athlete will be encouraged to continue pedaling to maintain adequate venous return and to perform an active 10 to 15 minute cool down at 50 watts. Although the test end-point is ultimately up the subject, the researchers will verbally encourage the athletes to give a maximal effort throughout the test.

During the GXT oxygen consumption, carbon dioxide production, ventilation rate, heart rate and rhythm, and oxyhemoglobin saturation will be measured every minute. Perceived exertion will be measured two minutes into each workload and blood lactate will be measured at rest, over the last minute of each workload, and 2 minutes post exercise.

Computer assisted indirect calorimetry will be used to assess oxygen consumption, carbon dioxide production, and ventilation rate. Heart rate and rhythm will be monitored each minute using an 8-lead ECG. Oxyhemoglobin saturation will be measured using a forehead mounted pulse oximeter. Perceived exertion will be measured on the Borg 6-20 scale.

In order to measure blood lactate, a finger will be pricked using an adult Tenderlett® after being thoroughly cleaned with an alcohol swab. Through the pricked finger, approximately 50 μl of blood will be drawn into a 75 μl capillary tube. Using a micropipette, 25 μl of this blood will be transferred to a 250 μl micro-centrifuge tube containing a 50 μl buffer and lysing solution. After mixing the blood and solution in the micro-centrifuge tube, a 25 μl sample will be immediately drawn into a YSI 2700 lactate analyzer for analysis of blood lactate. Approximately 500 μl of blood will be drawn from each subject during the GXT. All researchers involved with blood sampling or directly attending a subject will wear OSHA approved latex gloves, protective eye wear, and lab coats. Floors and workstations potentially in contact with blood will be covered by absorbent bench paper that will be changed for each test. All objects (Tenderletts, capillary tubes, micro-centrifuge tubes, gauze, alcohol swabs, absorbent paper, weighing dishes) coming in contact with blood or bodily fluids will be disposed of in appropriate biohazard waste containers for sharp and non-sharp objects. Biohazard waste will be picked up monthly by BFI waste in approved biohazard waste containers. After each test, the testing area and test equipment will be wiped down with a 10% bleach solution and then sprayed with an aerosol based pseudomonacidal, virucidal, mildewcidal, fungicidal, staphylocidal, and tuberculocidal agent (Cidecon® Disinfectent, o-phenylphenol & ethyl alcohol, Bryn Mawr, PA).

During all tests guidelines for exercise stress testing established by the American College of Sports Medicine will be strictly adhered to. Accordingly, exercise will be terminated when the athlete chooses to stop or if a researcher observes a potential test termination sign or symptom (e.g., abnormal ECG, nausea,
light headedness, cyanosis). All researchers involved in data collection will be trained in basic life support and emergency procedures.

For our particular population there are no contraindications to graded exercise stress testing. Furthermore, the procedures detailed are standard laboratory protocol approved previously by the University of Colorado at Boulder Human Research Committee.

**Body Composition Assessment**

After each subject’s GXT, they will be scheduled for a body composition assessment using a whole-body dual energy x-ray absorptiometry scan (DXA, Model DPX-IQ Lunar Corp., Madison, WI). The scan will be used to assess total and regional fat-free mass, fat mass, and bone mineral density. The total time commitment for the body composition assessment will be no more than 30 minutes.

**Resistance Measures (Aerodynamic/rolling resistance and frontal surface area)**

After the subject’s body composition assessment, subjects will be scheduled at their convenience for their frontal surface area assessment and aerodynamic and rolling resistance measures. If environmental conditions are favorable, the aerodynamic and rolling resistance measures will be performed before the frontal surface area assessment. Otherwise, digital photographs of the subject will be taken while pedaling between 50 to 100 watts on their personal bicycle mounted to a stationary trainer. A total of 15 pictures will be taken while the subject pedals with hands on the brake levers (hoods), on the bottom curve of the handlebar (drops), and in their level time trial position (time trial). The total time commitment for the pictures will be approximately 30 minutes.

All aerodynamic and rolling resistance measures will take place over a 1 km section of Independence road adjacent to the Boulder Airfield, in Boulder Colorado. Within this 1 km section of road we will mark a 200-meter section of road termed the collection trap (CT). Athletes will be asked to ride east and west through this trap in three distinct body positions (hoods, drops, and time trial) at three distinct power outputs for each body position (100 watts below level time trial power, level time trial power, and 100 W above level time trial power) for a total of 18 passes through the CT. Power output and velocity will be measured through the trap using a rear hub or crank based power meter. The total time commitment for this assessment will be no longer than 2 hours.

If the environmental conditions (i.e., wind speed) are not within the limits required for our protocol, subjects may have to be rescheduled for their aerodynamic and rolling resistance measures. In some cases, subjects may also have to be rescheduled while in the field due to a deterioration of the environmental conditions. Thus, it may take each subject more than a single appointment to complete this aspect of the study.

**D. Surveys, Questionnaires, and Interviews**
Medical History (Appendix C)

A medical history will be given to subjects to fill out during their first orientation meeting to screen for subjects with possible contraindications to strenuous exercise or with medical complications that may prevent them from completing the study safely.

Training History (Appendix D)

Subjects will be asked to fill out a training history questionnaire so that we can describe the experience level of our subjects and so that we can screen out subjects who do not meet the experience level required for the study.

Training Log (Appendix E)

Subjects will fill out a training diary during the familiarization period and during the weeks they are participating in the time trials and GXT. This information will be used so that we can properly describe the training load experienced by each athlete leading into the time trial and test as this may affect their performance during these tests.

Dietary Recall (Appendix F)

We will ask the subjects to fill out a dietary recall sheet for the three days leading into their first uphill time trial and during the day of the time trial. Because nutrition can greatly influence performance, we intend to record their dietary intake so that they can maintain the same diet leading into the subsequent time trial and GXT.

III. Risks and Benefits

A. Uphill and Level Time Trial

Risks

The risks involved with the time trials will not be greater than the risks the subjects face during their normal training and racing. During normal training and racing, however, there is always the risk of crashing. Accordingly, all precautions will be taken to provide the safest possible environment for the subjects. These precautions will include posting signs along the course warning motorists of cyclists along the road side, recruiting only experienced cyclists, and maintaining research
assistants along the course who are trained in basic life support and who will be carrying cell phones to contact emergency services. With these precautions and since subjects will not be asked to draft or ride in close proximity to one another, we believe that the risk of crashing during these time trials may even be lower than our subject’s normal training and racing.

Because of the intensity of exercise involved, there is always the risk of an abnormal response to exercise, including an abnormal blood pressure response, arrhythmias, syncope, and even death. Subjects will be carefully screened for any potential medical contraindications.

**Benefits**

The obvious benefit of the time trials is a specific and real world assessment of their performance where each individual athlete must work against resistance factors that are unique to them.

**B. Graded Exercise Stress Test**

**Risks**

The potential risks of a graded exercise stress test include the possibility of abnormal blood pressure, abnormal heart rhythms and fainting due to the sudden cessation of work. Discomforts may include nausea, shortness of breath, fatigue, light-headedness and muscle soreness 1 to 2 days after the test. Any symptom that threatens the safety of a subject will result in immediate termination of the test. In addition, all subjects will be allowed to stop exercise whenever they choose.

There are no known risks for the non-invasive measures taken during the GXT. There is a minimal risk, however, involved with blood draws through finger pricks. A small percentage of individuals experience light-headedness and fainting when exposed to blood. Also, some momentary pain will be felt while the finger is being pricked. Subjects will be warned of these risks and asked not to participate if they have experienced problems in the past with finger pricks or with the sight of blood. Finally, there is a risk of infection and the spread of disease through blood. Consequently, all precautions will be taken to maintain a sanitary environment and to properly handle all biohazard waste.

**Benefits**

The GXT will provide an opportunity for the athletes to explore their maximal work capacity under a controlled environment. More importantly, the physiological variables monitored may provide invaluable feedback to the subjects about their strengths, weaknesses and current fitness level. This information will give us the necessary physiological references along with their resistance to movement profile to better predict their future and present performance. This may ultimately help them to develop better training and competitive strategies to optimize their performance.
D. Body Composition Assessment

Risks

There is a small amount of radiation exposure (0.05 mRem) associated with the DXA which is less than 1/20 of a typical chest x-ray. The more radiation one receives over the course of one's life, the more risk of having cancerous tumors or of inducing changes in genes. The changes in genes possibly could cause abnormalities or disease in a subject's offspring. The radiation in this study is not expected to greatly increase these risks, but the exact increase in such risks is unclear.

Benefits

An athlete's mass and total body composition can have a significant impact on performance. In addition, it is an important baseline measure needed to accurately describe the characteristics of our subjects. Of particular interest, we have observed that many of our professional male cyclists from previous studies have bone density values below normal. Because the high level of training and non-weight bearing aspect of this sport may be the predisposing factor in these abnormal bone density values, the bone density measures from this assessment may help to identify a number of athletes with lower than average bone density.

E. Frontal Surface Area Assessment

Risks

None.

Benefits

Since an athlete's frontal surface area is an important component of an athletes' total aerodynamic resistance, measuring a subject's frontal surface area will allow us to better understand all the factors that influence aerodynamic resistance. More importantly, if the frontal surface area measures alone correlate highly with an athlete's true aerodynamic resistance and significantly improve our ability to predict cycling performance over physiological measures alone, then digital imaging may become a viable, simple, and inexpensive technique for greatly improving our ability to assess real world performance.

F. Aerodynamic and Rolling Resistance Measures

Risks

Because the efforts required for this assessment are very short, the physiological risk associated with this protocol are theoretically smaller than those
associated with the time trials and GXT. Of course, the athletes will be on their bicycle on an open road and will face the same risks as those associated with training.

Benefits

The major benefit of this protocol is that we will be able to measure the true aerodynamic and rolling resistance of each individual subject – a measure that has never been conducted in tandem with physiological measures and which would normally be assessed through limited and expensive wind tunnel testing.

IV. Privacy

The information and measurements obtained during all phases of this project will be treated as privileged and confidential. No information will be released or revealed to any person other than those directly involved as investigators in this research without the subject’s written consent. However, the data will be used for statistical analysis and scientific presentation with the subject’s privacy retained. All subjects will be coded and their identity protected through all phases of the project. Filing cabinets storing raw data will be locked. All computers used in the study and individual computer documents will be password protected.

V. Investigators Qualifications

The investigators in this study have previously received Human Research Committee approval at the University of Colorado at Boulder for all the procedures detailed in this study. To date, the investigators have completed these procedures without incident and are confident in their ability to maintain a safe, confidential, and positive environment for past and future subjects.
Informed Consent for Predicting Uphill and Level Time Trial Performance

Applied Exercise Science Laboratory
3100 Marine St., Room A40
554 UCB, Administrative Research Center
Boulder, CO 80309-0554

Statement of Informed Consent

Project Title:
Predicting performance using physiological and resistance to movement variables

Investigators:

PI: William Byrnes, PhD (303-492-5301, byrnes@spot.colorado.edu)
Co-PI: Allen Lim, MS (303-735-1358, limh@colorado.edu)

Purpose and Significance:

Your velocity and performance is ultimately determined by your ability to produce power and the aerodynamic and gravitational forces that resist forward motion. Accordingly, to properly predict your individual time trial performance it would be necessary to assess both of these factors. Unfortunately, laboratory tests used to predict performance tend to focus solely on the physiological determinants of power while ignoring the influence of weight and aerodynamics. Thus, the purpose of this study is to predict uphill and level time trial performance by assessing your physiological and aerodynamic profile. Our hypothesis is that understanding these two key variables together is more predictive of real world time trial performance than either variable alone. To our knowledge, this will be the first attempt to conduct a study of this design and is significant because it holds the potential of substantially improving our ability to predict performance in cycling, helping athletes like yourself to optimize performance in the sport of cycling.

Project Overview:

Phase 1 – Orientation Meeting and Pre-Study Meeting: Week 1 (2 hours)
Before participating in this study you will be required to attend a one-hour orientation meeting where the purpose, methods, risks and benefits of this study will be detailed. After reviewing this informed consent and asking any questions you may have about the study you will be asked if you would like to participate.  

If you chose to participate, you will be rescheduled for a pre-study meeting where your medical history and training history will be reviewed. If you show no medical conditions that might disqualify you from the study and fit the experience level we are looking for, then you will be scheduled for your first time trial. At this time your bicycle will be equipped with a Power Tap® power meter for use during this study and you will be fully instructed in its use.

**Phase 2 – Familiarity Period: Weeks 1-2**

Before your first time trial, you will use the power meter in training for a 1 to 2 week period to become familiar with its operation. During this period you will also need to pre-ride each time trial course and to begin tracking your ride duration, average power output, average heart rate, total work done, and rating of perceived exertion (1-10 scale) in a training diary provided to you.

**Phase 3 – Field Time Trials: Weeks 3& 4 (2 hours)**

After the familiarity period, your first time trial will be an uphill time trial on a Saturday or Sunday morning followed by a level time trial a week later. Three days prior to time trial events and on the day of the time trial your diet will need to be recorded in a journal that will also be provided to you. To control for the influence of nutrition on time trial performance you will be asked to replicate this recorded diet prior to your second time trial and your laboratory test. After completing your level time trial you will be scheduled for a laboratory test within one week.

**Phase 4 – Laboratory Testing: Week 4 (2.5 hours)**

In the laboratory, the first test that will be performed will be a graded exercise stress test where your maximal oxygen consumption (VO₂ max), blood lactate threshold (LT), efficiency, electrocardiogram, and the content of oxygen in your blood stream will be measured from rest to maximal exercise.

After your stress test you will be rescheduled for a body composition assessment where your fat mass, fat-free mass, and bone density will be measured.

Finally, at the time of your stress test or at another pre-scheduled time, digital pictures will be taken of you in different cycling positions to measure your frontal surface area on the bicycle.

**Phase 5 – Aerodynamic and Rolling Resistance Measures: Week 5 (2 hours)**

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2 Subject Initials ___
After completing the GXT and body composition assessment, you will be scheduled for your aerodynamic and rolling resistance measures. Because these measures require that there is relatively no wind, this aspect of the study is being placed last because it is not a time sensitive measure. You may be re-scheduled for this assessment more than once in order to assure that the appropriate environmental conditions are met.

**Phase 6 – Feedback:**

Within one month of completing the study, your results will be given back during a 1-hour private meeting with one of the principle investigators.

**Description of Methods: Attendant Risks, Discomforts and Benefits.**

**I) Field Time Trials:**

The uphill time trial will occur first on a Saturday or Sunday morning and will take place on Flagstaff road from 17th street on Baseline Road to the top of the climb 15 km up at 6,904 feet. The total elevation gain for this climb is 1,416 feet. The expected time on this climb will range from 30 to 45 minutes. The level time trial will occur a week after the uphill time trial and begin at 75th and Hygiene road, going east to Airport Road, west on Nelson road, and North along 75th back to Hygiene for a 4.34 km lap. Just over 9 laps will be performed for a distance of 40 km. The total elevation gain and fall over each lap of this course is 157 feet. The expected time to complete this time trial will range from 50 minutes to 60 minutes.

In the three days leading up to the time trials and on the day of the time trial, you will be asked to record your diet and to prepare as you would normally prepare for any time trial competition. In the three days leading up to your level time trial, you will replicate your pre-uphill time trial diet and training routine. On the day of both time trials you will be required to use the power meter to record your effort but you will not be allowed to see your data during either time trial.

Because we are on open roads, you are responsible for following traffic laws and using common sense to protect the safety of yourself, other participants, and the researchers. Riders who do not wear an ANSI approved helmet will not be allowed to participate. Three research assistants will be present at your time trials -- one at the bottom, one at the middle of the course, and one at the top. Not only will they be there to time your effort they will also be present to aid you in case of a mishap or accident. If you get a flat tire during the event, you will be given an opportunity to redo the time trial within a week.

**Risks Associated with the Field Time Trials:**

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The risks involved with the time trials will not be greater than the risks you face during your normal training and racing. Because of the intensity of exercise involved, there is always the risk of an abnormal response to exercise, including an abnormal blood pressure response, arrhythmias, syncope, and even death. Beyond the risks associated with intense exercise, there is also the risk of bodily harm or death due to an accident or mishap. All precautions will be taken to provide the safest possible environment for you. However, it is ultimately your responsibility to use caution and good judgment while riding on open roads.

**Benefits Associated with the Field Time Trials:**

The benefit of the time trials is that we will achieve a specific and “real world” assessment of your performance where the resistance is unique to your own body type. With the advent of cycle mounted power meters, performing these tests in the field also gives us the opportunity to measure the true power required to perform in these distinct events.

**II) The Graded Exercise Stress Test:**

**Exercise Protocol:**

After a 15-minute warm-up at 50 to 100 watts, the first stage, lasting four minutes, will begin at a workload of 150 watts. Every four minutes the workload will be increased by 30 watts until you reach a maximal level of exertion or request to stop. Immediately after the test you will be continually monitored and asked to complete a 10-15 minute cool down consisting of light pedaling at 50 to 100 watts.

All stress tests will be monitored by Allen C. Lim, MS a certified exercise test technologist through the American College of Sports Medicine. During all tests, Mr. Lim will be assisted by an undergraduate or graduate research assistant.

The graded exercise stress test is a single test that will occur during a single session at the Applied Exercise Science Laboratory located in room A53 in the Administrative Research Center on East Campus (3100 Marine Street).

**Risks and Discomforts associated with a Graded Exercise Stress Test:**

The potential risks of a graded exercise stress test include the possibility of abnormal blood pressure, abnormal heart rhythms and fainting due to the sudden cessation of work. Discomforts may include nausea, shortness of breath, fatigue, light-headedness and muscle soreness 1 to 2 days after the test. Any symptom that threatens your safety will result in immediate termination of the test. You may choose, however, to terminate the test at any point in time.

**Benefits of a Graded Exercise Stress Test:**

Despite the potential risks and discomforts, there are benefits of a graded exercise stress test. This test provides an opportunity for you to explore your maximal
work capacity under a controlled environment. In addition, three variables -- VO₂
max, lactate threshold, and economy -- that will be measured during the test are highly
predictive of cycling performance and may provide you with insight on your potential
strengths and weaknesses in the sport of cycling.

Measurement of Oxygen Consumption:

In order to measure submaximal and maximal oxygen consumption you will
be asked to place a rubber mouthpiece similar to a snorkel in your mouth during
exercise. This mouthpiece will be attached to a respiratory valve connected to hosing
that leads to a gas analyzer and a ventilation meter. During this procedure, your nose
will be sealed with a nose plug. Because you will not be able to talk during this
process due to interference by the mouthpiece the attending staff and researchers will
communicate with you through yes and no questions and with a chart that lists a
gradation of exertion levels (rating of perceived exertion scale). The collection of
accurate data is dependent upon secure placement of the mouthpiece and nose plug
during the entire duration of exercise. However, if at any time you feel constricted or
need to communicate essential information concerning your welfare please feel free
to remove the apparatus.

Risks and Discomforts Associated with the Measurement of Oxygen Consumption:

There are no known risks of oxygen consumption measurement. The
mouthpiece, however, can often cause temporary dryness of the throat. To help
alleviate this, you will be allowed to remove the mouthpiece and nose clip for the first
minute of each workload to drink and clear your throat.

Benefits of Oxygen Consumption Measurement:

The benefits of oxygen consumption measurement include the ability for us to
calculate the oxygen required for a given power giving you an indication of your
economy or gross mechanical efficiency. Economy along with lactate threshold and
your maximal oxygen consumption can be a strong indicator of performance and help
you understand some of your physiological strengths and weaknesses. Also, oxygen
consumption is directly linked to caloric expenditure and thus the number of calories
burned for any given workload can be calculated and correlated to your heart rate and
power output.

Measurement of Heart Rate and Heart Rhythm:

Heart rate and rhythm will be measured with an electrocardiogram (EKG).
Before the stress test, six electrodes will be applied to your torso and chest. To apply
these electrodes your skin will be cleaned with alcohol and an abrasive similar to find

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sand paper will be lightly rubbed across each location to decrease resistance. Also, any hair underlying the location of the electrodes will be removed with an electric razor.

The electrocardiogram will provide us with a continuous electronic display of your heart that will allow us to continually monitor if your heart is functioning properly. If any disturbances in your heart’s rhythm are observed we will immediately stop the test.

The EKG results will be read by Allen C. Lim. Mr. Lim is certified by the American College of Sports Medicine to assess potential EKG contraindications to exercise stress testing. Should any abnormalities arise on the resting EKG the stress test will not be performed and the EKG will be given to you and your personal physician who will make any potential recommendations.

**Measurement of Blood Lactate:**

Lactate threshold will be analyzed through blood samples taken through finger pricks over the last minute of each stage during the submaximal exercise stress test. Approximately 2-3 drops of blood will be taken per stage. The total number of finger pricks will be dependent upon the total number of submaximal stages you are able to complete. Normally, the total number of finger pricks range from a minimum of 3 to a maximum of 8 pricks. The total amount of blood taken will range from 250 $\mu l$ to 500 $\mu l$.

*Risks Associated with the Measurement of Blood Lactate:*

The risks of blood draws through finger pricks are minimal. A small percentage of individuals experience light-headedness and fainting when exposed to blood. Some momentary pain will be felt while the finger is being pricked. If you have experienced fainting at the sight of blood in the past, please inform the investigators.

**Benefits of Blood Lactate Measurement:**

The benefits of blood sampling include the assessment of your lactate threshold which is a strong predictor of performance in cycling and which can be used as a physiological reference point to gauge training and racing intensities.

**Measurement of Oxyhemoglobin Saturation:**

During the stress test we will also measure oxyhemoglobin saturation, which is essentially a measure of the percentage of oxygen being transported in the blood. We will take this measure with a device called a pulse oximeter. First your forehead will be cleaned with alcohol. Then a sensor that emits varying wavelengths of light

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will be taped to the forehead. Oxyhemoglobin saturation will be continually monitored during the graded exercise stress test.

**Risks Associated with Measurement of Oxyhemoglobin Saturation.**

Pulse oximetry measurements are completely non-invasive. Thus, there are no known risks or discomforts associated with pulse oximetry measurements.

**Benefits of Oxyhemoglobin Saturation Measurement:**

This measure will allow us to determine if your pulmonary system rate limits your maximal aerobic capacity.

### III. Body Composition Assessment:

After your stress test you will be scheduled to have your percent body fat and bone density determined using a whole-body dual energy x-ray absorptiometry scan (DXA, Model DPX-IQ Lunar Corp., Madison, WI). This assessment will take place in Carlson Gymnasium at the University of Colorado at Boulder main campus.

There is a small amount of radiation exposure (0.05 mRem) associated with the DXA which is less than 1/20 of a typical chest x-ray. The more radiation one receives over the course of one's life, the more risk of having cancerous tumors or of inducing changes in genes. The changes in genes possibly could cause abnormalities or disease in a subject's offspring. The radiation in this study is not expected to greatly increase these risks, but the exact increase in such risks is unclear.

### IV. Frontal Surface Area Pictures:

On the day of your stress tests or at another scheduled time we will take digital pictures of you in different cycling positions while you ride a trainer indoors. The positions will include riding in the hoods, drops, and in time trial bars or on your time trial bicycle.

### V. Aerodynamic and Rolling Resistance Assessment:

The aerodynamic and rolling resistance assessment will need to take place when there is relatively no wind. In our experience we have found that this typically occurs very early in the morning (6 am to 9 am) or in the evening (6 pm to 8 pm). As such, it is likely that this assessment will be scheduled for the early morning or late evening.

Aerodynamic and rolling resistance will be calculated by measuring your power and speed (using your road and TT bicycle) while cycling along a 1 km section of Independence road adjacent to the Boulder air field. On each bicycle you will ride in both the east and west direction at a power output corresponding to 100 watts.

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above, 100 watts below and exactly at your level time trial power output. For each power output on your road bicycle you will ride in both the hoods and drops. If you don not have a time trial bicycle, the aerodynamic position you assumed on your road bike will also be utilized during this assessment. Otherwise an assessment on your time trial bicycle will also be performed.

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Inquires:

Any questions about this project and the measurements involved are welcomed and encouraged. If you have any doubts or concerns please ask for further explanations. Questions regarding your rights as a subject can be directed to the Human Research Executive Secretary at the Graduate School of the University of Colorado Boulder (303-492-7401). Upon request, you may also receive a copy of the institution's general assurance from the Human Research Executive Secretary. Questions may be directed to any of the listed investigators.

Confidentiality:

The information and measurements obtained during all phases of this project will be treated as privileged and confidential. No information will be released or revealed to any person other than those directly involved as investigators in this research without your written consent. However, the data may be used for statistical analysis and scientific presentation with your right to privacy retained. To ensure confidentiality the following measures will be implemented:

1) During your laboratory testing the laboratory will remain private and closed to the public. Only research assistants involved in the study and individuals you give written or verbal consent to witness your test will be allowed to observe the test.

2) During all other testing procedures other subjects may be present, however, your data or personal results will not be revealed to any subject or individual not involved as a researcher in this study unless you give us written or verbal consent to do so.

3) During your participating in this study your identity on all forms and documents containing data that will be analyzed or collected will be coded as a randomly assigned number.

4) All data and results will be locked in secure offices. Any data on computers will be password-protected.
Injury and Compensation:

As a volunteer subject in this study you will not be monetarily compensated for your participation or time.

In addition, as a subject in this study you acknowledge that bicycling is an inherently dangerous sport and fully realize the dangers of participating in cycling on open roads and fully assume the risks associated with such participation including, by way of example, and not limitation, the following: the danger of collision with pedestrians, vehicles, other riders, and fixed or moving objects; the dangers arising from surface hazards, equipment failure, inadequate safety equipment, weather conditions, and the released parties’ own negligence; and the possibility of property loss, and serious physical and/or mental trauma or injury associated with bicycling and related activities. For yourself, your heirs, executors, administrators, legal representatives, assigns, and successors in interest (collectively "Successors") YOU HEREBY WAIVE, RELEASE, DISCHARGE, HOLD HARMLESS, PROMISE NOT TO SUE AND INDEMNIFY the University of Colorado, Department of Kinesiology and Applied Physiology, students, research assistants, and faculty associated with this study (collectively, the "Released Parties") from any and all rights and claims including claims arising from the released parties’ own negligence, which you have or which may hereafter accrue to you and from any and all damages which may be sustained by you directly or indirectly in connection with, or arising out of your participation in or association with participating in, travel to, or return from events associated with this study. You hereby consent to receive medical treatment which may be deemed advisable in the event of injury, accident, and/or illness during this study. You have no physical or medical condition which to your knowledge that would endanger others or yourself during your participation in this study.

Freedom to Consent:

Your participation in this project is completely voluntary and you are free to deny consent. If you decide to participate, you may rescind this decision during any stage of the project.

The investigators have read and understood the General Guidelines on the Rights and Welfare of Human Subjects (Senate Document 79-012), and agree to comply with all clauses to the best of their ability. In addition to considerations described in this document, the investigators fully intend to conduct all procedures in a manner that ensures your safety and comfort.

I have read this form in its entirety, or it has been read to me, and I understand the procedures in which I will be engaged. I hereby consent to participate in this project.

Signature ________________________________ Date __________
Witness ________________________________ Date __________