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Physiological Effects of Varying Power Output in a Cycling Time Trial

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PHYSIOLOGICAL EFFECTS OF VARYING POWER OUTPUT IN A CYCLING TIME TRIAL

by

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ABSTRACT

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During a bicycle time trial, varying power slightly to counter external conditions may result in improved performance [Swain, 1997], but it is not known if such power variations result in added physiological stress. Thus, the purpose of this study was to determine if variable power (VP) cycling produced greater physiological stress than constant power (CP) cycling of the same mean intensity. Eight trained male cyclists (age 28 ± 2 yr, mass 74.4 ± 2.3 kg, $\dot{V}O_{2max}$ 4.24 ± 0.13 L·min^{-1}, weekly training 277 ± 44 km) performed three 1 h ergometer trials. The first trial was performed at a self-paced maximal effort. The mean power from that trial was used to determine the power for the CP trial (constant effort at mean power) and the VP trial (alternating between ± 5% of mean power every 5 min). No differences were found between the CP and VP trials in mean $\dot{V}O_2$ (CP 3.33 ± 0.11 L·min^{-1}, VP 3.26 ± 0.12 L·min^{-1}), mean heart rate (CP 158 ± 3 min^{-1}, VP 159 ± 3 min^{-1}), mean blood lactate concentration (CP 4.2 ± 0.7 mM, VP 4.3 ± 0.7 mM), or mean RPE (CP 13.9 ± 0.4, VP 14.1 ± 0.4). Therefore, during a strenuous 1 h effort (78% of $\dot{V}O_{2max}$), subjects experienced no additional physiological stress by varying power ± 5% compared to a constant power effort.

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INTRODUCTION

Problem Description

In bicycle racing, the time trial is commonly referred to as the "race of truth". It is a pure test of cycling strength where ability and conditioning determine the winner, and not the use of team tactics or drafting, which are so important in mass-start races. While the metabolic and biomechanical factors which enable one person to ride a bicycle faster than another have been well documented [Hagberg et al., 1979; Miller and Manfredi, 1987; Coyle et al., 1988; Coyle et al., 1991; Hawley and Noakes, 1992; Loftin and Warren, 1994], little research has been performed investigating how to pace oneself in order to ride a bicycle a certain distance in the shortest amount of time.

On flat roads and on a calm day, achieving the fastest possible time would be done by maintaining a constant power output producing the highest sustainable speed for the duration of the race [Swain, 1997]. Variations in that speed caused by equal uphill and downhill segments, or equal upwind and downwind segments, serve to increase the total time. The primary reason is that when equal distance is covered at the faster and slower speeds caused by the wind or by the terrain, more time is lost travelling at the slower speed than is gained travelling at the faster speed. For example, a cyclist pedaling at 40 $km \cdot h^{-1}$ travels 10 km in 15 min. If the cyclist decreases speed during the first 5 km to 35 $km \cdot h^{-1}$ and increases speed during the second 5 km to 45 $km \cdot h^{-1}$, the overall time required to ride the 10 km distance rises to 15 min 14 s (first 5 km: 8 min 34 s; second 5 km: 6 min 40 s).

Additionally, on a course where the uphill/downhill or upwind/downwind segments were of equal length and severity, a cyclist pedaling at a constant power who is slowed from 40 $km \cdot h^{-1}$ to 35 $km \cdot h^{-1}$ by a grade or headwind would fail to reach 45 $km \cdot h^{-1}$ on the corresponding downhill/downwind section. Air resistance increases with the square of speed, meaning that a force acting against a cyclist causes a greater change in speed than a force of equal magnitude acting in the direction of the cyclist's motion.

Popular advice given to time trial riders is that riding at the highest sustainable constant power output, as indicated by heart rate or oxygen consumption, is the most effective strategy for riding the fastest possible time trial [Matheny, 1989]. Research supports this method, provided that the ride takes place in the absence of wind or hills - ideal conditions virtually never seen in a road-course time trial. In theory, when racing on an outdoor road course, the rider should attempt to minimize the variations in speed produced by wind and hills as much as possible. Computer simulations using various combinations of rider ability, grade, and wind speed have shown that, on courses with alternating and equal uphill/downhill or upwind/downwind segments, increasing power on the uphill (or upwind) segments by as little as 5% and decreasing power on the downhill (or downwind) segments while maintaining constant mean power will indeed reduce the time necessary to finish the course [Swain, 1997]. Often, time trial courses are of an "out-and-back" or circuit nature, satisfying the equal uphill/downhill requirement, and potentially the equal upwind/downwind requirement of the simulations.

While varying power results in enhanced performance in a computer simulation, the

simulation does not account for possible increased physiological stress incurred by varying power. Variations in power should result in a decreased efficiency in accomplishing work, as seen with an accumulated O_2 deficit at the start of exercise, and an excess O_2 consumption post-exercise.

Statement of Purpose

The aim of this study is to determine whether or not the strategy of varying power according to grade or wind conditions can be used by a trained cyclist without causing greater physiological stress than riding at a constant power output. The subjects will first perform a maximal one-hour trial to determine P_{HOUR}, the highest mean power output sustainable for that duration. Once P_{HOUR} has been determined, the subjects will perform two time-trial rides of 1 h duration in random order. The constant-power trial will be at a power output of 100% P_{HOUR}. The variable-power trial will alternate ± 5% from 100% P_{HOUR} every 5 min throughout the trial. The subjects will perform an equivalent amount of work during each trial.

Four indicators of physiological effort will be recorded periodically throughout the trials: heart rate (HR), oxygen consumption (VO_2), blood lactate concentration ([HLa]), and rating of perceived exertion (RPE). Each of these four variables will be tested for significant difference between the steady state and variable-intensity trials.

Hypothesis

Athletes trained in cycling will complete the two time-trial rides, at variable and constant workrates, without significant differences in mean HR, mean $\dot{V}O_2$, mean [HLa], and mean RPE.

Limitations

During the preliminary screening for major coronary risk factors [ACSM, 1995], no blood testing will be performed. Instead, the subjects will be relied upon to indicate their own serum cholesterol levels, if known.

It is impossible to fully simulate competitive cycling in the laboratory. The subjects in this study will most likely lack some of the motivation to perform well that is supplied by competition, and their attention may wander due to the fact that they will not have to concentrate on controlling their bicycles. The physiological response to riding on the SensorMedics ergometer will probably differ slightly from the subjects' normal response, due to the unfamiliar riding position. The test protocol also simulates a "perfect world" situation, one where the sections performed at a higher power output are of the exact duration as those performed at a lower power output.

The average $\dot{V}O_2$ which actually occurs during 5-min stages in the variable-power trial may not be equal to the mean obtained from the first and last 75 s of each 5-min period.

Operational Definitions

Dependent Variables:

Mean HR (Mean Heart Rate): the mean of all heart rate measurements for a single subject during a trial. HR will be recorded continuously over 15-s periods during the first 75 s and last 75 s of each 5-min stage in the variable-power trial, and will be recorded during the corresponding elapsed times during the constant-power trial.

Mean $\dot{V}O_2$ (Mean Oxygen Consumption): the mean of all $\dot{V}O_2$ measurements for a single subject during a trial. $\dot{V}O_2$ will be recorded continuously over 15-s periods during the first 75 s and last 75 s of each 5-min stage in the variable-power trial, and will be recorded during the corresponding elapsed times during the constant-power trial.

Mean [HLa] (Mean Blood Lactate Concentration): the mean of all [HLa] measurements for a single subject during a trial. [HLa] will be measured from a blood sample drawn during the final 30 s of each stage of the variable-power trial, and at the corresponding elapsed times during the constant-power trial.

Mean RPE (Mean Rating of Perceived Exertion): the mean of all RPE measurements for a single subject during a trial. RPE will be measured following removal of the mouthpiece, which will occur 75 s into each 5-min stage in the variable-power trial, and at the corresponding elapsed times during the constant-power trial.

Other Terms:

P_{OBLA} (Power at Onset of Blood Lactate Accumulation): the workrate during an incremental exercise test at which the subject's [HLa] first reaches a level of 3 mM.

$\dot{V}O_{2max}$ (Maximal Oxygen Consumption): the highest $\dot{V}O_2$ obtained over any continuous 60-s time period during an incremental exercise test, with respiratory exchange ratio (RER) $\geq$ 1.10.

CHAPTER II

LITERATURE REVIEW

Areas of Research

In order to gain background knowledge about the physiological changes and/or adaptations occurring when power output is varied during exercise, several areas of research should be explored. This review will examine research concerning the following:

- What physical factors determine the energy cost of cycling?
- In an event of 30-60 min duration and near-maximal intensity, what physiological factors limit the athlete's performance?
- What are the physiological responses to interval exercise as compared to continuous exercise?
- From a physiological and performance standpoint, is there an "optimal" strategy for expending effort in a bicycle time trial?

It is important to note that while this study will focus on one particular aspect of competitive cycling, the conclusions reached here can be applied to many other cycling events. For example, while in a paceline or within a pack where the riders are constantly shuffling positions, a cyclist experiences dramatic changes in the effects of aerodynamic drag. When a rider rotates to the front of a paceline at 40 $km \cdot h^{-1}$, an immediate 25-30% increase in power output is necessary to maintain speed (based on results of a study by

McCole et al., 1990); pulling off and moving to the back of the line requires a similar decrease in power. This cycle may be repeated numerous times in succession. As the cyclist moves from a protected position in a pack towards the edge or the front, an increase in power output of as much as 40% may be necessary to keep pace [McCole et al., 1990].

Factors Determining the Energy Cost of Cycling

In level cycling, the rider must perform work to overcome the factors of air resistance, rolling resistance, and mechanical resistance within the bicycle. According to Kyle [1996], energy loss due to mechanical resistance ranges from 2 to 4%, an amount small enough to be considered negligible in the research listed below. Two adjustments to the required amount of work may be necessary: addition of work performed while riding uphill, and extra work required to accelerate the bicycle from a standing start. The results of several studies have quantified these variables through mathematical principles and/or experimentation.

At the time-trial speed of a trained cyclist, air resistance (R_a) is the most prominent obstacle to forward progress; R_a comprises at least 90% of the total resistance to motion against a bicycle at speeds of 40 $km \cdot h^{-1}$ or greater [Kyle, 1979]. R_a can be calculated using the following equation:

$$R_a = 0.5\, C_D\, A\, \rho\, (\upsilon_{ss} + \upsilon_w)^2$$

where C_D is the coefficient of drag, A is the projected frontal area of rider and bicycle, ρ is the air density, υ_{ss} is the velocity of the bicycle and rider relative to the ground, and υ_w is the

magnitude of the wind velocity along the direction of travel.

C_D is related to the shape of a cyclist's body and the ability of air to flow smoothly around it, and can be modified by riding position, clothing, and bicycle construction. A is related to the rider's surface area and the frontal area of the bicycle, and can be modified by riding position. ρ is proportional to barometric pressure, and inversely proportional to temperature.

Increases in a cyclist's velocity relative to the air quickly magnify air resistance and the power required to maintain pace. Because R_a increases with the square of velocity, a 2x increase in speed produces a 4x increase in R_a, a 3x increase in speed produces a 9x increase in R_a, and so on. Since power is equal to force times velocity, power (or the rate of energy utilization required to move against the force of air resistance) increases with the cube of velocity.

Rolling resistance (R_r) is the force produced against the direction of motion by the contact between the tires and the road surface. The magnitude of R_r depends largely on tire pressure and on the characteristics of the tires and the road surface [Whitt, 1971]. It is proportional to the weight of the cyclist plus bicycle, and is constant, regardless of speed. In the field, R_r has been measured on average cyclists with racing bicycles to be between 3 and 4 N [Di Prampero et al., 1979; De Groot et al., 1995]. To illustrate how minimal this force is, it is approximately equal to the force measured between the skate blade of a moving speed skater and the ice [De Koning et al., 1992]. At competitive speeds, R_r has much less effect on a cyclist than does R_a.

Riding on a course that finishes above its starting point increases the total amount of work performed by the cyclist. The work performed in riding up a hill is equal to the weight of the cyclist plus bicycle multiplied by the vertical distance [Olds et al., 1993]. Finally, an extra bit of work must be performed at the beginning of the trial in order to accelerate the bicycle to a steady-state speed. Work must be translated into kinetic energy for the bicycle, while overcoming the constantly increasing effect of R_a [Olds et al., 1993].

Di Prampero et al. [1979] experimentally determined a quantity labeled "tractional resistance", which will be explained below as the sum of R_a and R_r. The authors used a car to tow subjects on racing bicycles at a series of constant speeds ranging from 5 to 16.5 $m \cdot s^{-1}$, with a dynamometer placed in series on the cable connecting the bicycle to the car to measure the total drag force on the bicycle and rider. The tests were conducted on a calm day, to prevent added effects of wind. Tractional resistance (in N) was read directly from the dynamometer at the same point in all of the towing runs. Analysis of the data showed that tractional resistance (R_T) increased as a quadratic function of velocity ($r = 0.98$) according to the following regression equation:

$$R_T = 3.2 + 0.19\upsilon^2$$

Due to the fact that, by definition, R_r is a constant and R_a increases with the square of velocity, Di Prampero et al. interpreted the R_r of the test bicycles to be 3.2 N and R_a to be equal to $k\ \upsilon^2$, where k is equal to 0.19 $N \cdot m^{-2} \cdot s^2$. To determine the power output (P), tractional resistance is multiplied by ground speed (υ_{ss}) to yield the following equation:

$$P = 3.2\upsilon_{ss} + 0.19\upsilon^2\upsilon_{ss}$$

where P is in watts and υ_{ss} is in $m \cdot s^{-1}$.

Olds et al. [1993] brought the concept of mathematical modeling of cycling one step further: using a model to predict performance of elite track cyclists. The model attempted to relate the energy demand of cycling, derived in a similar manner to that done by Di Prampero et al., to the energy-producing capacity of a cyclist, which took into account the energy produced through aerobic and anaerobic processes. To test the model, the authors attempted to predict the performances of 18 elite track cyclists in the 4000-m individual pursuit.

The subjects performed three exercise tests to supply information for the model. First was an incremental test to exhaustion, beginning at 100 W and increasing 50 W every 5 min, to determine steady-state $\dot{V}O_2$ at each submaximal workload and overall cycling efficiency. Second was another incremental test to exhaustion, this time beginning at 200 W and increasing 25 W every 1 min, to determine maximal aerobic power. Finally, a supramaximal test performed at an estimated 115% $\dot{V}O_{2max}$ determined maximal accumulated oxygen deficit for the contribution of energy by anaerobic processes. These results, combined with routine anthropometric data, allowed the authors to predict performance in the 4000-m individual pursuit. Once the subjects performed the actual 4000-m test, the predictions were analyzed for accuracy.

There was a significant correlation between the predicted and actual results ($r = 0.803$, $P \leq 0.0001$). The mean absolute difference between the predicted and actual results was 7.7 s, or 2.3% of the mean 4000-m time. While the results were encouraging, the

authors discussed several possible methods for improving the predictive ability of the model. The relationship between velocity and time during initial acceleration has not been established; in order to simplify the model, the authors made an assumption that acceleration at the beginning of the 4000-m trial is constant, which is unlikely. Also, in defining R_a the authors used the value for k found by Di Prampero et al.: 0.19 $N \cdot m^{-2} \cdot s^2$; the effects on C_D of differing cycling clothes and racing bicycles was not considered.

Olds et al. [1995] tackled the more complex problem of predicting performance in a 26-km road time trial. The mathematical representation of the energy cost of cycling used in the 1993 study was enhanced to include corrections for headwinds, crosswinds, relative humidity, and rotational kinetic energy of the cranks, wheels, and cyclist's legs. Also, the value for C_D used in the model was an estimate for the subjects in the Di Prampero et al. [1979] study determined by using both the body surface area (A_b) of those riders and an equation developed by Olds et al. that relates A_b to frontal area. Finally, initial acceleration was assumed to be represented by a monoexponential function, in order to simulate more accurately the varying amount of power necessary to overcome R_a. Other enhancements were made to the energy supply side of the model as well.

The subject group testing this model consisted of 41 experienced cyclists, 32 men and 9 women. As in the 1993 study, these subjects performed a series of exercise tests prior to the road time trial in order to acquire the data used in the model. An incremental test to exhaustion was used to determine $\dot{V}O_{2max}$ and ventilatory threshold; stages were 2 min in duration, and one of three different test protocols were used, depending on the expected

ability of the subject. Each subject also performed a mechanical efficiency test on two occasions. This test consisted of six 5-min incremental workloads designed to elicit an estimated 40-90% $\dot{V}O_{2max}$. The regression of $\dot{V}O_2$ on power output was used as a measure of cycling efficiency. Finally, the supramaximal test from the 1993 study was used to obtain the maximal accumulated oxygen deficit. Along with anthropometric data, these variables were used to predict performance on a 26-km road time trial.

The time trials were conducted on a flat 6.5-km course on which the subjects rode four lengths (turnaround times were not included). Temperature, relative humidity, wind speed, and wind direction were measured on site every 5-10 min, and barometric pressure, tire pressure, and wheel size were recorded for each subject. The cyclists used their own bicycles. About half of the cyclists used aerodynamic handlebars, and four cyclists used aerodynamic wheels (disk or trispoke wheels); no corrections were made for the use of either of these accessories.

The correlation between the predicted and actual performance times was significant ($r = 0.89$, $P \leq 0.0001$). The mean absolute difference between predicted and actual times was 1.65 ± 1.44 min or 3.87% of the mean actual time. With the subjects divided into four groups based on competitive level (recreational, club, state, national), analysis of variance revealed that there were significant differences ($P = 0.03$) in mean difference between actual and predicted times among the groups; post hoc analysis showed that the mean difference for the recreational cyclists (+1.90 min) was significantly different than those for the club (-0.09 min), state (+0.38 min), and national (-0.01 min) -level cyclists. The relative

inaccuracy for the recreational cyclists could be explained by the fact that those cyclists would be expected to have the worst sense of pacing.

The impressive results from the two studies by Olds et al. indicate that the factors determining the energy cost of cycling are well understood, and are able to be measured with great precision.

Physiological Factors Limiting Performance

Many researchers have attempted to determine the physiological factors that explain the success of some cyclists and the failure of others. Some of these studies are presented below.

Hagberg et al. [1979] gathered data on nine national class American cyclists in order to compare them to elite European cyclists who typically outperformed the Americans in competition. In addition, the subjects were split into two groups: those who had been selected to the American World Team (n = 4) and those that had not (n = 5). A maximal cycle ergometer test revealed no difference in $\dot{V}O_{2max}$ between the two groups; in addition, the mean $\dot{V}O_{2max}$ for all of the subjects, 70.3 ± 2.0 $ml \cdot min^{-1} \cdot kg^{-1}$, was similar to published findings for groups of elite East German, Dutch, and Swedish cyclists. The differences in performance between the American and European cyclists, or between the American World Team members and nonmembers, could not be accounted for by $\dot{V}O_{2max}$; other factors would need to be considered.

Miller and Manfredi [1987] acknowledged previous findings that $\dot{V}O_{2max}$ was a

strong predictor of cycling ability; they attempted to identify other variables that would also contribute to success. A total of 15 physiological and anthropometric variables were defined and measured on each of 22 male competitive cyclists. Each subject then completed a 15-km time trial on a flat out-and-back course. Nine of the 15 variables, including $\dot{V}O_{2max}$, training volume, vital capacity, and biking experience, were significantly related to performance time. Analysis using stepwise regression revealed that 87% of the variance in performance could be explained solely by ventilatory threshold measured in $ml \cdot min^{-1} \cdot kg^{-1}$; adding a body circumference ratio (thigh+calf:arm+chest) provided the only significant improvement (93% of variance, $P < 0.05$ over VT alone) in model accuracy.

Coyle et al. [1988] divided 14 male endurance athletes into two groups (H and L) according to their lactate threshold expressed in $\%\dot{V}O_{2max}$. The average lactate threshold of the H group ($81.5 \pm 1.8\%$ of $\dot{V}O_{2max}$) was significantly higher ($P < 0.001$) than that of the L group ($65.8 \pm 1.7\%$ of $\dot{V}O_{2max}$). Each subject performed an exercise bout to exhaustion on a cycle ergometer at a constant workrate of 88% of $\dot{V}O_{2max}$. The recorded times were positively related ($r = 0.90$, $P < 0.001$) to lactate threshold, a relationship similar to that found by Miller and Manfredi [1987]. The average time to fatigue in the H group (60.8 ± 3.1 min) was more than twice that of the L group (29.1 ± 5.0 min). Blood samples drawn at the conclusion of exercise showed that the lactate concentration of the subjects in the H group (7.4 ± 0.7 mM) was about half that of the L group (14.7 ± 1.0 mM). Analysis of vastus lateralis samples revealed a correlation between capillary density and time to fatigue ($r = 0.74$, $P < 0.003$). It was theorized that increases in capillary density result in faster

removal of lactic acid from working muscle and delayed fatigue; however, there was no correlation between capillary density and $\%\dot{V}O_{2max}$ at lactate threshold. The combination of those two variables accounted for >93% of performance variation in the ride to exhaustion at 88% of $\dot{V}O_{2max}$.

Loftin and Warren [1994] used a similar criterion to divide the subjects for comparison purposes; after the 18 subjects (male, USCF category III or IV) completed a graded $\dot{V}O_{2max}$ and ventilatory threshold test, the six cyclists with the highest ventilatory thresholds (in $\%\dot{V}O_{2max}$) formed the H group, while the six lowest formed the L group. The subjects later performed a simulated 16.1-km time trial on their own bicycles while attached to a Velodyne Trainer. Group H, whose cyclists had higher ventilatory thresholds than those in group L (76.9 ± 4.0 vs. 68.0 ± 2.8 $\%\dot{V}O_{2max}$; $P \leq 0.05$), completed the time trial in less time than did group L (16.29 ± 2.08 vs. 20.93 ± 3.33 min; $P \leq 0.05$). Ventilatory threshold and body composition were found to be correlated with time trial performance (both $P \leq 0.05$).

Coyle et al. [1991] investigated physiological and biomechanical characteristics of elite cyclists, looking for variables that could explain the performance differences among the group. The authors tested 15 male competitive cyclists who were racing at USCF category 1 or 2. The group selection criterion and the testing protocol were different than in the 1988 study. The subjects were divided into two groups based on their fastest 40 km time trial performance recorded on a flat sea level course during the previous 12 months; those who rode the trial in 56 min or faster were placed in group 1 ("elite-national class") and the

slower riders formed group 2 ("good-state class"). During the first of two laboratory sessions, the subjects performed standard $\dot{V}O_{2max}$ and blood lactate response tests; also, the pedaling technique of the subjects was analyzed using a pedal dynamometer capable of measuring normal and tangential forces applied to the pedal. During the second session, the subjects performed a test to determine the highest average power output that could be maintained for 1 h. The first 8 min of the test were performed at a preselected power output based on the results of the lactate threshold testing; after that the subjects were allowed to vary both the flywheel resistance on the ergometer and their cadence as desired. Following the test, samples of vastus lateralis muscle were taken for analysis of fiber type, capillary density, and enzyme concentrations.

For all of the cyclists, time trial performance was significantly correlated with the average power output maintained during the laboratory test ($r = -0.88$; $P < 0.001$). Time trial performance was also correlated with the average $\dot{V}O_2$ maintained during the laboratory test ($r = -0.834$; $P < 0.001$), and average power output during the laboratory test was best correlated to $\dot{V}O_2$ at lactate threshold ($r = 0.93$; $P < 0.001$). When analyzing the differences between the groups to determine possible factors affecting performance, the authors found that 40-km time trial performance was 10% faster in group 1 than in group 2 (53.9 ± 0.5 vs. 60.0 ± 1.1 min; $P < 0.01$). Also, during the laboratory test, group 1 maintained a power output that was 11% higher than the output of group 2 (346 ± 7 vs. 311 ± 12 W; $P < 0.05$).

The laboratory test also showed that group 1 maintained a marginally higher average relative $\dot{V}O_2$ than did group 2 (89.7 ± 1.1 vs. 85.8 ± 1.6 $\%\dot{V}O_{2max}$; $P = 0.06$). All 15

subjects were able to maintain an average $\dot{V}O_2$ for one hour that was higher than their lactate threshold. In fact, the average $\dot{V}O_2$ maintained by both groups during the laboratory test, when converted to $\%\dot{V}O_{2max}$, was approximately 10% higher than their lactate threshold.

Other significant differences between the elite-national class cyclists (group 1) and the good-state class cyclists (group 2) were found in the composition of the vastus lateralis muscle. The cyclists in group 1 were found to have a higher percentage of type I fibers (66.5 ± 3.7 vs. $52.9 \pm 5.7\%$; $P = 0.05$) and greater capillary density (464 ± 25 vs. 377 ± 22 capillaries per mm^2; $P < 0.05$). Analysis of pedaling technique revealed that the group 1 cyclists generated a larger peak torque on the pedals during the downstroke (76.8 ± 7.6 vs. 62.8 ± 13.8 N·m; $P < 0.05$). While the groups did not differ in the number of years that they had trained for cycling, the cyclists in group 1 had performed endurance training for a longer period of time (8.8 ± 0.9 vs. 5.0 ± 3.0 yr; $P < 0.01$).

Hawley and Noakes [1992] examined the relationships between peak power output vs. $\dot{V}O_{2max}$, and peak power output vs. 20-km time trial performance. The subject pool consisted of 100 cyclists and triathletes (54 men, 46 women) who trained at least four times per week, and who competed regularly at provincial- to world-class events. The subjects first completed a graded maximal test to exhaustion where $\dot{V}O_{2max}$ and peak power output were determined; the highest workrate completed was taken as the peak power output. Later, 19 of the subjects completed an outdoor 20-km time trial for comparison with peak power output. The results showed that peak power output was significantly related to both

$\dot{V}O_{2max}$ ($r = 0.97$; $P < 0.0001$) and time trial performance ($r = -0.91$; $P < 0.001$).

From the studies examined above, research has determined that those people who are considered to have high cycling ability generally have a high $\dot{V}O_{2max}$; however, this variable cannot differentiate between the elite cyclists and the good ones. The top cyclists are capable of riding at a higher percentage of their $\dot{V}O_{2max}$ before reaching their lactate threshold, and can both generate a higher peak power output and maintain a higher average power output for an extended period of time. They can produce higher peak torques while pedaling, and have a higher percentage of type I muscle fibers in the vastus lateralis muscle along with a greater capillary density. The differences in muscle composition could be a result of long-term endurance training; Coyle et al. [1991] reported that the percentage of type I fibers was highly correlated with the number of years of endurance training with the legs ($r = 0.75$; $P = 0.001$).

Interval vs. Continuous Exercise

Much is known about the induced effects of interval training, an invaluable part of the distance athlete's training program which is commonly used to raise the workload corresponding to the onset of blood lactate accumulation (P_{OBLA}). The protocol for the current study differs from most interval training routines in that during the low-intensity periods, the athlete is continuing to work at a reasonably high level (95% P_{HOUR}), instead of either resting or working at a moderate level. This section will examine the acute physiological effects seen during interval exercise of various exercise and rest workrates,

compared to those seen during similar amounts of work performed continuously.

Åstrand et al. [1960] were among the first to compare equivalent amounts of interval and continuous work. In their study, a single well-trained male subject performed a number of trials where a total of 64800 kgm of work was done on a cycle ergometer over the course of 1 h. In the continuous trials, a workrate of 1080 kgm·min^{-1} was used, or a load on the cycle ergometer of 3 kg at 60 rev·min^{-1}. Each interval trial consisted of equal work and rest periods of 0.5, 1, 2, and 3 min totaling 30 min each. The workrate performed in the work period was 2160 kgm·min^{-1}, or a load of 6 kg at 60 rev·min^{-1}, and was 0 during the rest period.

An interesting fact about this study is that the authors hypothesized that the trials with the longer work/rest periods would result in lower accumulation of lactic acid than would the shorter work/rest trials, because the longer work periods would give the body time to raise oxygen intake to meet the work demand, while in the shorter work periods the body would be constantly adding to the oxygen debt. The data did not support this hypothesis; during the 0.5 min work/rest trial, the subject's [HLa] at the end of the trial was 2.2 mM, very close to the level after 1 h of continuous work (1.3 mM). [HLa] rose substantially with each increase in work/rest duration, reaching 13.4 mM after the 3-min work/rest trial. Other measures of physiological stress, such as heart rate, $\dot{V}O_2$, and ventilation, showed similar patterns as that of [HLa]; at the shortest work/rest durations, these measures were only slightly above those for the continuous trial, while the longer work/rest durations produced much higher stresses.

The authors found these results to be of great interest. By using short work/rest durations, one could work large muscle groups at a very high power without greatly increasing the stress on the respiratory and cardiovascular systems. Longer durations would result in a training effect not only on the large muscle group, but on the respiratory and cardiovascular systems as well.

Christensen et al. [1960] conducted a similar experiment to the Åstrand et al. study, with the major differences being the mode of exercise (treadmill running), a shorter total duration for the exercise protocols (30 min), and a wider variety of work/rest combinations. Two well-trained male subjects participated in the study. At the end of each work period, the subject would jump off of the belt, which was moving at 20 $km \cdot h^{-1}$, and land with one foot on either side of it. When the rest period was concluded, the subject would jump back onto the moving belt and immediately continue at 20 $km \cdot h^{-1}$.

This study demonstrated that interval exercise enabled the subjects to perform large amounts of work at high intensities with considerably less physiological stress as compared to continuous exercise. Using 10 s work periods and 5 s rest periods, one of the subjects was able to run 6.67 km in 30 min; with the treadmill set at the same speed (20 $km \cdot h^{-1}$), the subject was nearly exhausted after 3 min of continuous running. Increasing the length of the rest periods to 10 s reduced the distance traveled in 30 min to 5.00 km, but postexercise [HLa] was reduced to only 2.2 mM, only slightly above resting level.

In the intermittent trials where the work:rest ratio was 1:1, [HLa] in the subjects showed a marked increase during the first 5 min, but increased slowly or even leveled off

during the remaining 25 min. Also, the authors found it remarkable that, at a workload corresponding to a $\dot{V}O_2$ of 5.00 $l \cdot min^{-1}$, the RQ for the experiment averaged 0.88 ± 0.03.

Fox et al. [1969] attempted to determine the sources of metabolic energy used during both interval and continuous exercise. Six trained male subjects performed a variety of interval and continuous treadmill running protocols. In the first phase of testing, the subjects performed a continuous run to exhaustion followed by interval runs resulting in the same total amount of work, but using several work/relief time patterns. In the second phase, several of the subjects performed identical interval runs to those completed in the first phase, but with additional repetitions to raise the total amount of work performed to 2-2.5 times greater than the continuous run to exhaustion at the same intensity. Additionally, several subjects repeated interval runs with moderate-intensity work-relief periods (9.6 $km \cdot h^{-1}$ at 2% grade; approx. 60% $\dot{V}O_{2max}$) substituted for the normal rest-relief periods. In most of the experiments, $\dot{V}O_2$, oxygen debt, and [HLa] were monitored throughout exercise and into recovery.

The authors found that the major difference in the metabolic energy sources between the two types of exercise is that interval exercise induces a much greater contribution from the ATP/CP system than does continuous exercise. On the basis of the percentage of total metabolic energy, the additional contribution of the ATP/CP system appears to produce a roughly equal decline in the contributions from aerobic and glycolytic sources. The results also showed that the oxygen debt and [HLa] were always lower during interval exercise than when the same amount of work was performed continuously. During the interval runs with

shorter total work durations (up to 60 s), net $\dot{V}O_2$ during the work periods was the same regardless of whether the subject was performing interval or continuous exercise; during a trial with a continuous run of 300 s, $\dot{V}O_2$ for the continuous work period was 2.6 l greater than that for the interval work periods due to the subject reaching $\dot{V}O_{2max}$ by the 3rd min of continuous exercise. All of the subjects who performed interval runs of 2-2.5 times the total work of the continuous run were able to complete the additional work before [HLa] became comparable to levels found during the continuous run.

Of some relevance to the proposed study are the following trials from the Fox et al. [1969] study. At a speed of 20.8 $km \cdot h^{-1}$ and a grade of 2%, subject MG performed two trials: after 5 min of continuous work at that intensity, MG's [HLa] (5 min postexercise) was approximately 14.6 mM; after five repetitions of 1 min work/1 min rest intervals, MG's [HLa] (also 5 min postexercise) was approximately 9.0 mM. Two other subjects performed work/relief trials where work consisted of 1 min at 21.6 $km \cdot h^{-1}$ and 2% grade, and relief consisted of 2.5 min at 9.6 $km \cdot h^{-1}$ and 2% grade. During the last of five work/relief repetitions, subject RK recorded [HLa] of 6.2 mM, while [HLa] of subject MS measured 8.4 mM. While the inconsistencies between tests make definite conclusions impossible, these results indicate that variable-power exercise at a high level may, at worst, be no more strenuous than comparable constant-power exercise.

Hermansen and Stensvold [1972] investigated whether lactate was produced and/or removed during submaximal exercise; the intensities used during testing reached levels comparable to the low variable-intensity periods in the proposed study. Seven well-trained

subjects (3 male, 4 female) performed preliminary $\dot{V}O_{2max}$ testing on a treadmill, followed by a series of nine tests. Four of the tests consisted of 30 min of continuous treadmill exercise at 30, 60, 70, and 80% $\dot{V}O_{2max}$, with blood samples drawn every 5 min. The other five tests examined recovery after maximal intermittent exercise. These tests began with 3 bouts of running at the highest possible speed (female subjects: 17.4-18.6 $km \cdot h^{-1}$; male subjects: 21.6-23.4 $km \cdot h^{-1}$) lasting 60 s each, with 4 min of rest in between. Following the third test, the subjects performed either 30 min of continuous treadmill exercise at 30, 60, 70, and 80% $\dot{V}O_{2max}$, or 30 min of rest. Blood samples were drawn at 5 min intervals during the continuous exercise or rest.

During the continuous tests, only two of the seven subjects showed pronounced increases in [HLa] at the highest workloads (approx. 82-83% $\dot{V}O_{2max}$). During the recovery tests, [HLa] declined more quickly during all of the continuous exercise intensities than during rest. The authors calculated that the maximal rate of lactate removal occurred at 63% $\dot{V}O_{2max}$; at higher intensities, all subjects showed a pronounced rate of removal, although the rate of lactate removal at the highest intensity (80% $\dot{V}O_{2max}$) was significantly higher than at rest. Graphical representation of [HLa] versus time was supplied for two of the seven subjects; while it is unclear exactly when during recovery the blood samples were drawn, the graphs indicate a possible concern in terms of the proposed study. [HLa] does not begin to decline during the first several minutes after the maximal bout, and may possibly increase during that period. The proposed methodology calls for 5-min stages of variable-intensity exercise; it may be that longer stages (10-15 min) would allow more adequate recovery

time, and thus be physiologically easier to maintain.

The studies summarized above all agree that interval exercise produces no more physiological stress than continuous exercise of equal intensity and work output; in many cases, much less stress is observed. Granted, during the rest or "work-relief" stages none of the studies required their subjects to perform at intensities as high as those in the proposed study, with the possible exception of Hermansen and Stensvold [1972]. While Hermansen and Stensvold report that "it should be emphasized that an appreciable amount of lactate is removed even at work loads demanding 80-90% of an individuals' maximal oxygen uptake" [p. 198], it remains to be seen whether or not this effect will be seen during the 5-min lower-intensity intervals specified in the proposed methodology.

Time Trial Strategy

As discussed earlier, Swain [1997] modeled the physiology of a cyclist using equations presented by Di Prampero et al. [1979] to test the theoretical effects of varying power output based on grade and wind conditions. Two different courses were simulated. The first was 10 km in length, with alternating 1-km uphill and downhill segments of equal grade; the grade was set to 0%, 5%, 10%, and 15% during various trial simulations. The other course was 40 km in length, with alternating 5-km upwind and downwind segments. The wind speed on the upwind and downwind segments was always equal, and was varied between 0, 8, 16, and 24 $km \cdot h^{-1}$ during different trial simulations.

The "subjects" were three simulated cyclists, each possessing different ability as determined by maximum net $\dot{V}O_2$ ($\dot{V}O_2$ above resting level) that could be maintained for the test duration: 3, 4, and 5 l·min^{-1}. Each cyclist rode each course four times, once at a constant $\dot{V}O_2$, and once each at three different levels of $\dot{V}O_2$ variation: 5%, 10%, and 15%. In the trials using $\dot{V}O_2$ variation, $\dot{V}O_2$ was increased by the given amount over the base value during the uphill or upwind segments. During the downhill or downwind segments, $\dot{V}O_2$ was decreased by a sufficient percentage under the base value to result in a mean $\dot{V}O_2$ equal to the base value. The percentage decrease was always larger than the percentage increase due to the cyclist spending less time riding the downhill and downwind sections of the course.

The results showed that constant power output produced the fastest times when no wind effects or elevation changes existed. For example, the 4 l·min^{-1} cyclist rode the 40-km course in 58 min 10 s at constant $\dot{V}O_2$, and in 58 min 19 s with 15% variation in $\dot{V}O_2$. However, in the trials where wind and grade were present, each increase in the level of $\dot{V}O_2$ variation produced a faster time than the previous level. As the hills or wind became more severe, the time savings increased as well. The time savings were largest in each instance for the 3 l·min^{-1} cyclist and decreased as ability improved; however, the 5 l·min^{-1} cyclist also realized significant time savings under all grade and wind conditions.

Foster et al. [1993] used trained subjects to address the issue of optimal pacing in a 2-km time trial. The various methods of pacing were defined by controlling the speed at which the subjects rode the first km, then allowing them to ride the second km as quickly as

possible. Analysis of prior competitive events showed that only rarely was the first km of a 2-km time trial completed in less than 48% or more than 55% of the total time. Riding the first km in 51% of the total time was determined to provide an even pace over the 2-km distance, following initial acceleration. Subjects rode one trial at each of five predetermined starting paces, which were labeled very slow (first km approx. 55% of total), slow, even (first km approx. 51% of total), fast, and very fast (first km approx. 48% of total).

The even pace produced the fastest time (2.77 ± 0.18 min). Statistically, the even pace was significantly ($P < 0.05$) faster than the very slow, fast, and very fast paces. Additionally, the authors measured postexercise [HLa] and accumulated oxygen deficit in the subjects and found no significant differences between any of the trials, despite the differences in finishing time.

CHAPTER III

METHODOLOGY

Subjects

Subjects were recruited among cyclists who had competed in at least one USCF-sanctioned cycling event in category IV or above during 1996 and 1997, and triathletes who had competed in at least one sanctioned multisport event containing a cycling portion during the same period. Subjects were also required to be male, between 18 and 40 yr of age, and deemed to be apparently healthy by satisfying each of the following criteria as specified by the American College of Sports Medicine [ACSM, 1995]:

(1) No known cardiac/pulmonary/metabolic disease

(2) No symptoms suggesting the possibility of such disease

(3) No more than one major coronary risk factor.

Nine athletes met the criteria, were informed of the nature and risks of the study, and provided written informed consent in accordance with institutional guidelines for research with human subjects. One subject contracted a viral infection prior to the completion of the study, and his data were not considered in the statistical analysis.

The subjects were instructed not to perform any strenuous exercise during the 24 hours prior to testing, and to avoid food, caffeine, and other drugs during the three hours prior to testing. In order to reduce the risk of thermal stress and dehydration during testing,

they were also instructed to consume a minimum of 400 ml of water 20 min before the start of testing, in accordance with ACSM recommendations for exercising in excess heat and humidity [ACSM, 1995].

Instrumentation

Cycle Ergometery

All testing was performed on one of two machines: either a SensorMedics model 800 electronically braked and calibrated cycle ergometer (Yorba Linda, CA), or a Monark 818E mechanically braked and calibrated ergometer (Varberg, Sweden). The Monark ergometer was used during a portion of the study when the SensorMedics device was inoperative; each subject used the same ergometer for both the CP and VP trials.

The saddle of each ergometer was adjusted to provide approximately 5 degrees of bend in the knee at full extension. During all tests the subjects were required to maintain a constant cadence of approximately 90 $rev \cdot min^{-1}$. This cadence was found by Hagberg et al. [1981] to be the preferred and most economical cadence for highly trained, competitive cyclists pedaling at 80% $\dot{V}O_{2max}$. On the SensorMedics ergometer, the subjects attached their own clipless pedals; due to incompatible pedal threads on the Monark ergometer crankarms, those subjects who rode that machine used the supplied pedals and straps.

Measurement of Metabolic Data

Prior to each preliminary test and experimental trial, the subjects were fitted with a

mouthpiece (Hans Rudolph, Kansas City, MO) for the collection of expired air. The expired air was collected during portions of each trial and analyzed for the determination of ventilation ($\dot{V}_E$), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$) using a SensorMedics 2900c metabolic cart (Yorba Linda, CA). The O_2 and CO_2 analyzers of the metabolic cart were calibrated prior to each test against known gas concentrations, and the ventilation meter was calibrated at least once per day against a 3.0 L syringe. The subjects also wore ECG electrodes placed in a lead CM5 configuration, for heart rate (HR) measurement performed on an automated ECG system (SensorMedics Max-1, Yorba Linda, CA).

Measurement of [HLa]

Venous blood samples (5 ml) were drawn from the subjects before and during the maximal test and the two experimental trials through a 22G teflon catheter (Angiocath, Becton Dickinson, Sandy, UT) inserted into an antecubital vein. Catheter patency was maintained by periodic injection of a heparin/saline solution (2000 U NaHep in 10 ml 0.9% NaCl). Obtained samples were placed in ice packs for a maximum of 5 min, then spun down in a centrifuge for 10 min. Following that, 250 µl of plasma was drawn from the top of each sample; 10 µl of this was then drawn and placed on a lactate slide (Johnson & Johnson Clinical Diagnostics Inc., Rochester, NY) that had been inserted into a Kodak DT60 blood analyzer (Eastman Kodak, Rochester, NY), which returned the lactate concentration of the sample within approximately 6 min. The calibration of the Kodak

DT60 was confirmed daily via analysis of two control samples (Kodatrol, Johnson & Johnson Clinical Diagnostics Inc., Rochester, NY) representing low and medium concentrations, and by analysis of a high-concentration pooled sample drawn immediately following a pilot graded maximal test.

In order to prevent thermal stress, ambient temperature was maintained at 20-22 °C, and a large fan was directed at the subject for the duration of each test. During the one-hour trials the subjects were encouraged to drink water during the periods when collection of expired air was not taking place. The amount of water consumed during the experimental trials was recorded.

Methods

Overview

The subjects performed a total of four sessions in the Old Dominion University Human Performance Laboratory, with each of the final three sessions being separated by a minimum of 3 d. Preliminary data were gathered during the first two sessions for determination of the experimental protocol, and the two experimental trials were performed during the last two sessions. Detailed testing protocols will be described in subsequent sections.

During the first session, the subjects were first informed of the procedures and risks of the experiment, and then provided written informed consent. Anthropometric data were then collected, including height, weight, and skinfold measurements for the estimation of

percent body fat [Pollock et al., 1980]. The subjects then performed a maximal graded cycle ergometer test to determine maximal oxygen consumption ($\dot{V}O_{2max}$) and the power output corresponding to onset of blood lactate accumulation (P_{OBLA}).

At the second session, the subjects performed the familiarization trial; a one-hour maximal ride designed to determine the highest average power that could be maintained by each subject for 1 h (P_{HOUR}). This trial served two purposes: first, to determine the power level that would make completion of the experimental trials difficult but manageable; second, to better familiarize the subjects to long duration rides on the ergometer while periodically having expired air collected.

The subjects then performed one experimental trial at a constant power output (CP trial) and the other at a variable power output (VP trial). The order of these two trials was randomly determined.

Measurement of $\dot{V}O_{2max}$ and P_{OBLA}

$\dot{V}O_{2max}$ and P_{OBLA} were determined via a maximal graded cycle ergometer test. This test was conducted in one-minute stages. The first several stages were pedaled at a sufficiently low intensity to make a pretest warmup unnecessary. The power output started at 25 W, and was increased by 25 W during each successive stage. The subjects continued to pedal until they either stopped on their own volition, or they could no longer maintain a cadence of 90 rev·min^{-1}. Following termination of the test, they cooled down at 50 W for a minimum of 2 min.

$\dot{V}O_{2max}$ was defined as the highest $\dot{V}O_2$ obtained over any continuous 60-s time period, provided respiratory exchange ratio (RER) was ≥ 1.10 or the data showed that $\dot{V}O_2$ had reached a plateau. Six of the subjects recorded RER values over 1.10, while two had their $\dot{V}O_2$ plateau prior to that point.

Blood samples were drawn immediately before the test and during the last 30 s of each stage for lactate analysis. [HLa] was graphed versus workload for determination of P_{OBLA}, which was defined as the power (interpolated to the nearest 5 W) where [HLa] first reached 3 mM.

Familiarization Trial

Prior to the trial, the subjects were instructed to pace themselves to obtain their best 1-h performance. The trial began with a 10-min warmup period during which the subjects rode 4 min at 30% P_{OBLA}, 3 min at 50% P_{OBLA}, and 3 min at 70% P_{OBLA}. Following the warmup, the subjects pedaled for 1 h at a cadence of 90 rev·min^{-1}. The subjects were required to maintain P_{OBLA} for the first 10 min of the trial. For the remaining 50 min, on each minute the subjects signaled the experimenter to change power output ± 5 W, or to leave it unchanged. If at any time the subject appeared to be reaching imminent exhaustion, the tester could decrease the workload by up to 20 W until the subject's condition improved. The average power output for the trial (P_{HOUR}), an intensity known to be near maximal but maintainable over a one-hour period, was used to determine the intensities of the two experimental trials.

In order to familiarize the subjects with use of the mouthpiece, $\dot{V}O_2$ was recorded during the same periods as in the two subsequent trials; that is, assuming that this test consisted of 12 5-min stages, $\dot{V}O_2$ was recorded during the first 75 s and last 75 s of each stage. HR information was made available to the subjects via either ECG or radial artery palpation during this trial.

Variable Power (VP) Trial

The subjects were given a 10-min warmup period prior to the test using the following protocol: 4 min at 30% of P_{HOUR}, 3 min at 50% of P_{HOUR}, and 3 min at 70% of P_{HOUR}. The test required the subjects to pedal for 1 h at a cadence of 90 rev·min^{-1}; the workrate was changed every 5 min according to the following schedule (Table 1):

Table 1. VP Trial Protocol.

Time (min)	0	5	10	15	20	25	30	35	40	45	50	55
Power (% of P_{HOUR})	95	105	95	105	95	105	95	105	95	105	95	105

All subjects were able to successfully complete this trial on their first attempt.

HR and $\dot{V}O_2$ were recorded every 15 s during the first 75 s and the last 75 s of each 5-min stage. These values were averaged to provide a single value of HR and $\dot{V}O_2$ for each stage. Immediately after the mouthpiece was removed at the 75-s mark of each stage, the

subjects were asked to provide a rating of perceived exertion on the 6-20 scale developed by Borg [1982]. The subjects were encouraged to drink water ad libitum during the portion of each stage where $\dot{V}O_2$ was not being recorded. The total amount of water consumed during the trial was recorded. Blood samples were drawn for lactate analysis during the final 30 s of each stage. In addition to the stage-by-stage values of HR, $\dot{V}O_2$, [HLa], and RPE, an average value for each variable across the trial was recorded for each subject for reporting purposes.

Constant Power (CP) Trial

The subjects were given a 10-min warmup period prior to the test using the following protocol: 4 min at 30% of P_{HOUR}, 3 min at 50% of P_{HOUR}, and 3 min at 70% of P_{HOUR}. The test required the subjects to pedal for 1 h at 100% of P_{HOUR}, while maintaining a cadence of 90 rev·min^{-1}. All of the subjects were able to successfully complete this trial on their first attempt.

HR, $\dot{V}O_2$, [HLa], and RPE were recorded during the same periods as in the VP trial; that is, assuming that this test consisted of 12 5-min stages performed at a single intensity. Water was consumed and recorded as in the VP trial.

Since the subjects cycled at 100% of P_{HOUR} for 60 min, they performed the same total amount of work as in the familiarization trial (60 min at an average intensity of P_{HOUR}) and in the VP trial (105% of P_{HOUR} for 30 min and 95% of P_{HOUR} for 30 min).

Statistical Analysis

All statistical calculations were performed using Excel 97 (Microsoft, Redmond, WA). Four dependent variables measured during the two experimental trials were tested: HR, $\dot{V}O_2$, [HLa], and RPE. Two-way (2x12) ANOVAs for repeated measures were calculated to determine the presence of significant difference between the two experimental trials and between the 12 stages for each dependent variable; post hoc analysis via Tukey's test was used to determine which specific stages were different from each other. The alpha level was set at 0.05.

CHAPTER IV

RESULTS

Table 2 (Appendix A) presents characteristics of the subjects, including age, height, weight, body composition, and average training distance per week.

Table 3 (Appendix A) presents mean values for $\dot{V}O_{2max}$, RER_{max}, highest workrate completed on the maximal graded test (P_{max}), P_{OBLA}, and P_{HOUR}. Using a dependent student t-test, there was no difference found between P_{OBLA} and P_{HOUR}. P_{HOUR} was 69.3 ± 3.7% of P_{max}.

Table 4 (Appendix A) presents mean values for the dependent variables measured during the experimental trials. Analysis of variance showed no main effect between the CP and VP trials in $\dot{V}O_2$, HR, [HLa], or RPE. $\dot{V}O_2$ during the experimental trials averaged 78.5 ± 1.7% (CP) and 77.0 ± 2.4% (VP) of $\dot{V}O_{2max}$.

Analysis of variance showed a significant main effect for test duration, i.e. between 5-min stages, in all four dependent variables ($\dot{V}O_2$, HR, and RPE, $p < 0.001$; [HLa], $p < 0.05$). There was a gradual increase in the values for $\dot{V}O_2$, HR, and RPE throughout the 1-h trials. There was no change in [HLa] across time after the first 5 min of the trials was completed. These differences are noted as stage superscripts in tables 5a through 5d.

A significant interaction was found between stage and trial in three of the four dependent variables ($\dot{V}O_2$, HR, and [HLa], $p < 0.001$). Tables 5a through 5d (Appendix A),

and figures 1a through 1d (Appendix B), show stage-by-stage means for each dependent variable during each experimental trial. Stars in each figure denote stages where the dependent variable was significantly different between the two experimental trials.

$\dot{V}O_2$ during all six of the VP trial stages at 95% P_{HOUR} was significantly lower than during the corresponding stages of the CP trial. However, during all six of the 105% P_{HOUR} stages of the VP trial, $\dot{V}O_2$ was not significantly greater than in the corresponding stages of the CP trial.

Significant differences between the trials in HR occurred in stages 2, 6, and 8, where the VP trial stages (all at 105% P_{HOUR}) were higher than the CP stages. In all six 95% P_{HOUR} VP stages, HR did not differ from the corresponding CP stages.

[HLa] was significantly different between the trials in stages 2, 6, and 12, where the VP trial stages (all at 105% P_{HOUR}) were higher than the CP stages. In all six 95% P_{HOUR} VP stages, HR did not differ from the corresponding CP stages.

RPE was the only dependent variable that failed to have an interaction effect between trial and stage, as illustrated in figure 1d (Appendix B). No significant differences exist between the trials at any point.

A dependent student t-test revealed that there was no difference in the amount of water consumed during the two experimental trials (CP 528 ± 70 ml, VP 609 ± 56 ml).

CHAPTER V

DISCUSSION

Riders in this study did not experience significantly greater physiological stress when varying power output than when riding at a constant workload. Since the high-intensity stages of the VP trial were expected to be physiologically more difficult than the corresponding stages of the CP trial, the support of the hypothesis hinged on two questions. Would a power output of 5% below P_{HOUR} be low enough to permit some degree of recovery from the high-intensity stages? If so, would the five-minute duration of the stages be sufficient to allow the rider to recover to stress levels comparable to those maintained in the CP trial?

Based on findings from a study by Coyle et al. (1991) showing that highly trained cyclists can maintain mean intensities in excess of 85% $\dot{V}O_{2max}$ for 1 h, and on the fact that each of the experimental trials would require the subjects to perform an equal amount of work to that already completed in the preliminary 1-h trial, it was expected that the subjects would be able to successfully complete each of the experimental trials. Indeed, this was the case. $\dot{V}O_2$ in each of the low-intensity VP stages was significantly less than in the corresponding CP stage, while in the high-intensity stages $\dot{V}O_2$ rose only to the level measured during the CP trial.

This characteristic of the $\dot{V}O_2$ data is quite curious. Two points can be suggested to explain this. First, the length of the 105% P_{HOUR} VP stages may not have been enough time

for the riders to achieve steady-state $\dot{V}O_2$ consumption, with a portion of the increased power being supplied anaerobically. $\dot{V}O_2$ does not instantly increase to match the demand of an increase in power, therefore it may measure lower than expected for a period after such an increase. Any increase in power output comes with a cost in the form of oxygen debt, which results in an increase in the anaerobic energy component. In this case, evidence of an increased anaerobic component comes from increased [HLa] levels during the 105% P_{HOUR} VP stages, where all of the VP stages were higher than their CP counterparts, with the difference in three of those stages achieving statistical significance.

A second issue needing to be addressed concerning the observed $\dot{V}O_2$ data is the method of data collection. $\dot{V}O_2$ was measured during the first 75 s and last 75 s of each stage to allow the subject an opportunity to consume water during the midpoint of each stage. For this method to be completely accurate, the change in $\dot{V}O_2$ during the 5 min stage would have to be perfectly linear. In reality, after a power increase $\dot{V}O_2$ rises sharply for a period, then more slowly until reaching steady state. By assuming a linear relationship, the $\dot{V}O_2$ measurements during the 105% P_{HOUR} stages are probably lower than actual consumption. The opposite is likely true for the 95% P_{HOUR} stages; the measured values are probably higher than actual, due to the sharp drop in $\dot{V}O_2$ that occurs in response to a decrease in power output.

Taking these points into consideration, the actual differences in $\dot{V}O_2$ consumption in individual stages between the two trials may be more pronounced than what is reported in

these data. $\dot{V}O_2$ during the low-intensity VP trials is likely lower than what was calculated, and $\dot{V}O_2$ during the high-intensity VP trials is likely higher. The effect that these differences would have on mean $\dot{V}O_2$ for a trial is not known at this time. Further experimentation would be required to attempt to determine if increases and decreases in power output have similar but opposite effects on $\dot{V}O_2$ (which is the logical result of assuming linear change in $\dot{V}O_2$), or to what extent the effects differ.

While HR was measured at the same time as $\dot{V}O_2$, the data do not share the same characteristics. Unlike $\dot{V}O_2$, the only significant differences in HR between stages occurred in high-intensity VP stages and their corresponding CP stages. It appears that HR responds much more quickly to increases in power than does $\dot{V}O_2$. If this is the case, the difference in actual and reported HR during the 105% P_{HOUR} stages is greater than the difference in $\dot{V}O_2$, because the actual graph of the HR increase deviates even further from the assumed linear relationship.

The data for three of the four of the experimental variables showed a marked upward trend during the course of both the CP and VP trials. The exception was [HLa], which assumed a fairly consistent pattern of rise and fall in each trial from stage 3 to the end. The rise in $\dot{V}O_2$ and HR and the additional feelings of effort and discomfort reflected in RPE measurements over the course of the trial apparently were not connected at all with [HLa] levels.

In order to relate more closely to the time-trial cycling event, this study differs in

two ways from much of the prior research examining the physiological effects of variable-intensity exercise [Åstrand et al., 1960; Christensen et al., 1960; Fox et al., 1969]. First, the duration of the stages is considerably longer than in the prior research, which tested high- and low-intensity periods from 5 s to 3 min, the majority of which being 30 s or less. Second, while the previous studies used total rest periods or moderate workrate periods (up to 60% $\dot{V}O_{2max}$) as the low-intensity segments of a trial, in this study the subjects recovered at a relatively high workrate (~75% $\dot{V}O_{2max}$), obviously more typical of a competitive situation.

The results of this study support the variable power strategy proposed by Swain [1997] for cycling time trial performance. Swain demonstrated that the variable power strategy was effective at improving time-trial performance, assuming that the rider was capable of riding at the required intensities. The current study showed that, for the protocol performed here (deviations of ± 5% from P_{HOUR}), trained cyclists are indeed capable of maintaining those intensities for 1 h.

However, the testing protocol used here differs from competitive conditions. Athletes are routinely presented with a variety of grade and wind combinations that demand large changes in intensity over varying periods of time, such as a steep climb requiring near-maximal effort for 30 min followed by a 5 min descent where the rider need only to remain in an aerodynamic tuck. Further research in this area should use protocols where the high-intensity stages are considerably longer than the low-intensity stages, and where the workload during the low-intensity stages deviates further from the constant level than does

the high-intensity workload. These experimental designs reflect the relative amounts of time spent on the uphill and downhill parts of a climb, and the opportunity to ride at very low workloads without losing significant speed on a descent.

APPENDIX A

Table 2. Subject Characteristics.

	Age	Height (cm)	Weight (kg)	% Body Fat	Training Load ($km \cdot wk^{-1}$)
Mean	28	175	74.4	9.3	277
SE	2	3	2.3	1.1	44

Table 3. Test Results.

	$\dot{V}O_{2max}$					
	($L \cdot min^{-1}$)	($ml \cdot min^{-1} \cdot kg^{-1}$)	RER_{max}	P_{max}	P_{OBLA}	P_{HOUR}
Mean	4.24	57.1	1.11	378	266	259
SE	0.13	1.1	0.02	19	16	10

Table 4. Trials.

Trial		$\dot{V}O_2$ ($L \cdot min^{-1}$)	HR (min^{-1})	[HLa] (mM)	RPE
CP	Mean	3.33	158	4.2	13.9
	SE	0.11	3	0.7	0.4
VP (total)	Mean	3.26	159	4.3	14.1
	SE	0.12	3	0.7	0.4
VP (95% P_{HOUR} stages)	Mean	3.18	156	3.9	13.7
	SE	0.07	2	0.2	0.6
VP (105% P_{HOUR} stages)	Mean	3.35	163	4.7	14.4
	SE	0.02	2	0.1	0.4

Table 5a. $\dot{V}O_2$ by Stage.

	$\dot{V}O_2$ ($L \cdot min^{-1}$)			
	CP Trial		VP Trial	
Stage	Mean	SE	Mean	SE
1	3.01†	0.12	2.85	0.11
2[1]	3.26	0.12	3.26	0.13
3[1]	3.29†	0.12	3.19	0.13
4[1]	3.31	0.12	3.30	0.12
5[1]	3.31†	0.12	3.20	0.12
6[1,3]	3.34	0.12	3.34	0.12
7[1]	3.37†	0.12	3.23	0.12
8[1-3,5]	3.39	0.12	3.38	0.13
9[1,3]	3.40†	0.12	3.29	0.13
10[1-5,7]	3.41	0.13	3.40	0.14
11[1-3,5]	3.42†	0.13	3.31	0.13
12[1-7]	3.44	0.13	3.42	0.13

† Differs significantly from corresponding stage in VP trial ($p < 0.05$)

Superscripted numbers indicate the preceding stages that differ significantly from the stage in that column ($p < 0.05$)

Table 5b. HR by Stage.

	HR (min^{-1})			
	CP Trial		VP Trial	
Stage	Mean	SE	Mean	SE
1	148	3	146	4
2^{1}	153†	3	157	3
3^{1}	155	3	154	4
4^{1}	157	3	160	3
5^{1}	158	3	155	3
$6^{1-3,5}$	159†	3	163	3
7^{1-3}	160	3	159	4
8^{1-5}	161†	3	165	3
$9^{1-3,5}$	162	3	161	4
$10^{1-5,7}$	163	3	166	3
$11^{1-3,5}$	163	3	162	4
$12^{1-7,9}$	165	4	167	3

† Differs significantly from corresponding stage in VP trial ($p < 0.05$)

Superscripted numbers indicate the preceding stages that differ significantly from the stage in that column ($p < 0.05$)

Table 5c. [HLa] by Stage.

	[HLa] (mM)			
	CP Trial		VP Trial	
Stage	Mean	SE	Mean	SE
1	3.4	0.5	3.0	0.4
2	3.9†	0.6	4.6	0.6
3	4.2	0.7	4.1	0.6
4	4.1	0.7	4.6	0.6
5	4.3	0.7	4.1	0.6
6[1]	4.2†	0.8	4.8	0.7
7	4.4	0.8	4.2	0.8
8[1]	4.3	0.8	4.7	0.8
9	4.3	0.9	4.0	0.8
10[1]	4.2	1.0	4.7	0.9
11	4.4	1.0	4.1	0.9
12[1]	4.3†	1.0	5.0	1.1

† Differs significantly from corresponding stage in VP trial ($p < 0.05$)

Superscripted numbers indicate the preceding stages that differ significantly from the stage in that column ($p < 0.05$)

Table 5d. RPE by Stage.

	RPE			
	CP Trial		VP Trial	
Stage	Mean	SE	Mean	SE
1	11.1	0.6	10.9	0.7
2^{1}	12.5	0.5	13.1	0.6
3^{1}	13.1	0.5	13.0	0.4
4^{1}	13.4	0.4	13.5	0.4
5^{1}	13.6	0.4	14.0	0.4
6^{1-3}	14.3	0.4	14.3	0.4
7^{1-3}	14.3	0.5	14.5	0.4
8^{1-4}	14.6	0.4	14.9	0.4
9^{1-4}	14.8	0.5	14.8	0.6
10^{1-4}	14.8	0.5	15.1	0.5
11^{1-5}	15.3	0.5	15.0	0.5
12^{1-5}	15.3	0.5	15.4	0.6

No corresponding stages in experimental trials differ significantly ($p < 0.05$)

Superscripted numbers indicate the preceding stages that differ significantly from the stage in that column ($p < 0.05$)

Table 6a. $\dot{V}O_2$ Raw Data.

CP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	2.88	3.03	2.40	2.99	3.43	3.17	3.34	2.80
2	3.29	3.20	2.58	3.35	3.58	3.48	3.59	3.04
3	3.29	3.24	2.58	3.40	3.57	3.44	3.68	3.09
4	3.35	3.21	2.61	3.41	3.63	3.48	3.63	3.15
5	3.33	3.23	2.58	3.47	3.61	3.45	3.65	3.13
6	3.42	3.27	2.59	3.46	3.64	3.44	3.62	3.24
7	3.44	3.33	2.64	3.54	3.64	3.49	3.68	3.22
8	3.49	3.31	2.62	3.53	3.63	3.52	3.70	3.28
9	3.48	3.33	2.59	3.59	3.66	3.53	3.67	3.31
10	3.43	3.32	2.60	3.64	3.68	3.59	3.65	3.33
11	3.44	3.33	2.59	3.64	3.72	3.58	3.69	3.36
12	3.53	3.37	2.61	3.64	3.71	3.57	3.68	3.38

VP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	2.94	2.78	2.23	2.91	3.02	2.77	3.33	2.80
2	3.49	3.17	2.54	3.38	3.38	3.14	3.77	3.22
3	3.39	3.11	2.46	3.34	3.26	3.05	3.75	3.14
4	3.53	3.19	2.62	3.42	3.39	3.24	3.77	3.26
5	3.39	3.12	2.50	3.38	3.24	3.10	3.70	3.20
6	3.62	3.21	2.61	3.48	3.39	3.26	3.79	3.32
7	3.49	3.13	2.53	3.43	3.23	3.11	3.71	3.22
8	3.67	3.26	2.61	3.61	3.42	3.24	3.84	3.37
9	3.50	3.26	2.53	3.54	3.24	3.12	3.80	3.29
10	3.66	3.28	2.59	3.68	3.42	3.25	3.89	3.43
11	3.55	3.20	2.56	3.59	3.30	3.14	3.79	3.33
12	3.70	3.30	2.66	3.66	3.44	3.28	3.88	3.45

Table 6b. HR Raw Data.

CP Trial

	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	141	154	143	147	142	142	166	148
2	149	158	147	155	142	149	169	156
3	151	159	145	158	144	148	173	159
4	158	159	148	160	149	152	172	161
5	154	158	149	164	148	152	171	164
6	159	158	148	164	148	151	173	167
7	158	156	154	165	149	156	174	169
8	160	161	151	167	149	158	174	170
9	161	162	149	169	150	159	173	172
10	161	161	149	170	151	163	174	175
11	161	162	149	170	151	164	174	176
12	163	164	149	170	152	166	176	176

VP Trial

	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	133	159	137	148	140	134	164	152
2	146	166	146	158	152	150	173	161
3	141	165	145	156	150	146	172	158
4	151	168	151	159	159	157	173	163
5	141	165	147	158	150	150	169	162
6	152	170	152	163	161	159	175	170
7	144	165	150	160	154	151	174	171
8	154	169	157	166	160	158	177	177
9	146	169	154	160	154	154	173	174
10	155	169	158	165	162	161	177	178
11	146	162	156	163	158	156	176	178
12	158	167	158	166	165	159	178	182

Table 6c. [HLa] Raw Data.

CP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	4.2	2.2	4.9	2.8	2.3	1.9	3.6	5.4
2	4.8	2.3	3.7	4.9	2.2	1.9	4.1	6.9
3	4.9	2.7	4.4	5.4	2.6	1.7	4.2	7.9
4	4.9	2.5	4.0	5.4	2.7	1.7	3.9	7.7
5	5.2	2.8	3.9	5.6	2.8	1.7	4.1	8.4
6	5.1	2.7	3.4	5.6	2.8	1.5	4.2	8.5
7	5.1	2.6	3.7	6.1	2.8	1.7	4.3	8.9
8	4.6	2.5	3.0	6.4	2.6	1.8	4.2	8.9
9	4.2	2.5	2.7	6.9	2.6	1.9	4.1	9.6
10	3.8	2.5	2.5	6.9	2.5	1.9	3.8	10.0
11	3.9	3.0	2.7	6.9	2.5	2.1	4.0	10.4
12	3.7	2.6	2.4	6.7	2.4	2.2	4.0	10.6

VP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	2.5	2.8	3.6	2.7	2.1	1.5	4.0	5.0
2	4.3	4.1	4.7	4.8	3.0	2.2	6.1	7.3
3	3.6	4.3	4.0	4.4	2.4	1.6	5.7	6.5
4	4.1	4.5	4.3	5.2	2.8	2.3	6.1	7.8
5	3.4	4.1	3.6	4.7	2.4	1.6	5.2	7.5
6	4.1	4.8	4.5	5.7	2.7	2.1	5.7	8.8
7	3.0	4.4	3.7	4.9	2.1	1.6	5.4	8.3
8	4.0	4.3	4.0	5.9	2.5	2.1	5.6	9.5
9	2.9	4.0	3.2	5.3	2.1	1.7	4.4	8.7
10	4.0	4.1	3.4	6.0	2.4	2.3	5.0	10.3
11	3.1	3.5	3.1	5.0	2.2	1.6	4.4	10.2
12	4.3	4.0	3.4	6.4	2.4	2.3	5.1	11.9

Table 6d. RPE Raw Data.

CP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	9	12	12	11	9	10	12	14
2	12	12	13	12	13	10	13	15
3	13	12	13	13	15	11	13	15
4	13	13	14	13	15	11	14	14
5	14	13	14	14	14	11	14	14.5
6	14	13	15	15	15	12	15	15
7	14	13	15	15	14	12	16	15
8	14	13	15	15	15	13	16	16
9	14	13	15	16	14	13	16	17
10	14	13	15	15	14	14	16	17
11	15	13	16	16	14	14	17	17
12	15	13	15	16	15	14	17	17.5

VP Trial								
	Subject							
Stage	EH	GM	CB	MC	JE	TL	KJ	AB
1	9	12	13	11	8	9	12	13
2	13	13	14	12	13	10	15	15
3	13	12	15	12	13	12	13	14
4	13	13	16	13	14	12	14	13
5	13	13	16	13	15	13	15	14
6	14	13	16	14	14	13	15	15
7	14	13	16	14	16	13	15	15
8	14	13	17	15	16	14	15	15
9	14	12	17	14	14	15	16	16
10	14	13	17	15	14	15	17	16
11	14	13	17	14	15	15	16	16
12	15	13	18	15	13	16	17	16.5

Figure 1a. VO_2 During CP and VP Trials.

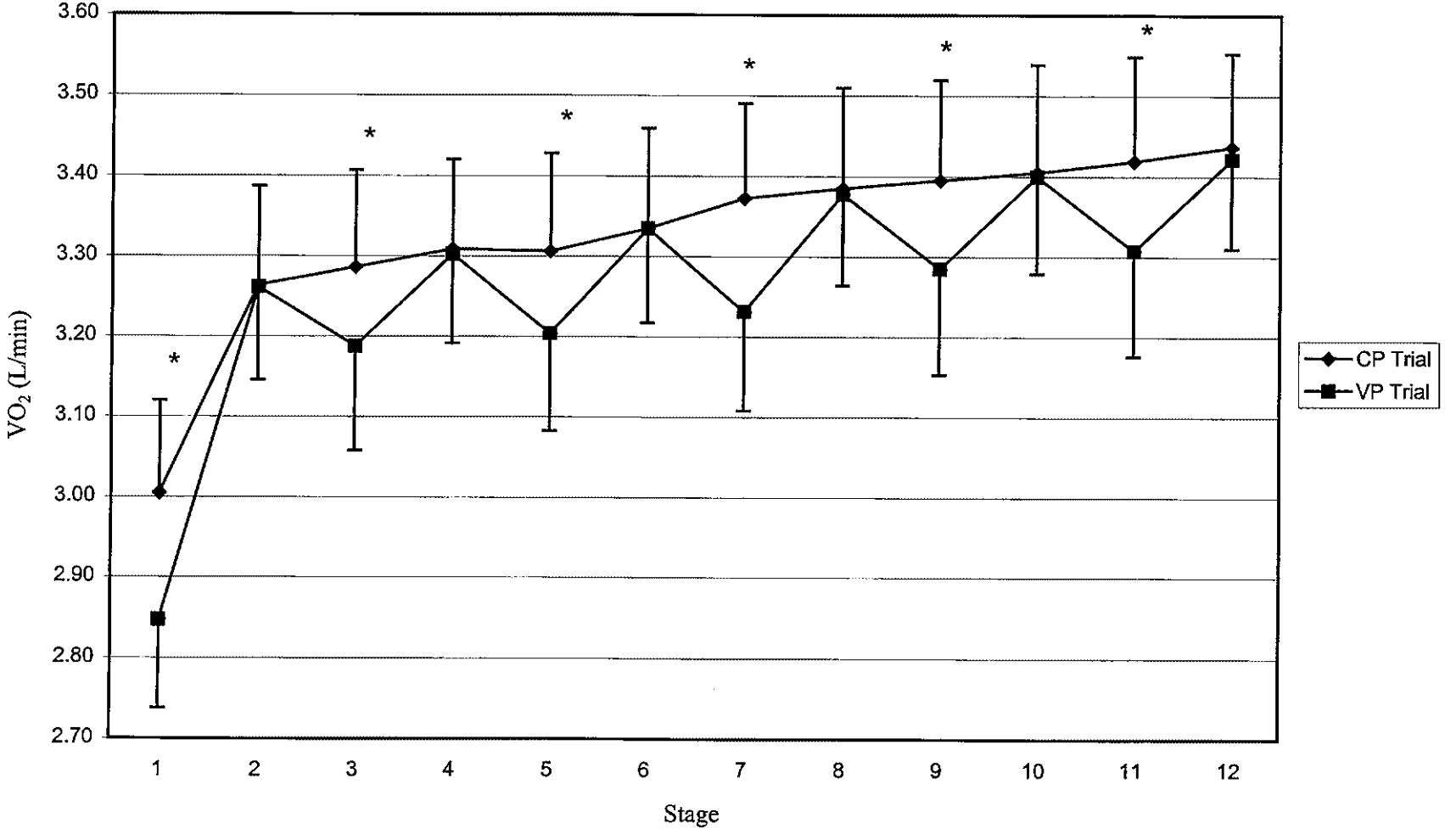


Figure 1b. HR During CP and VP Trials.

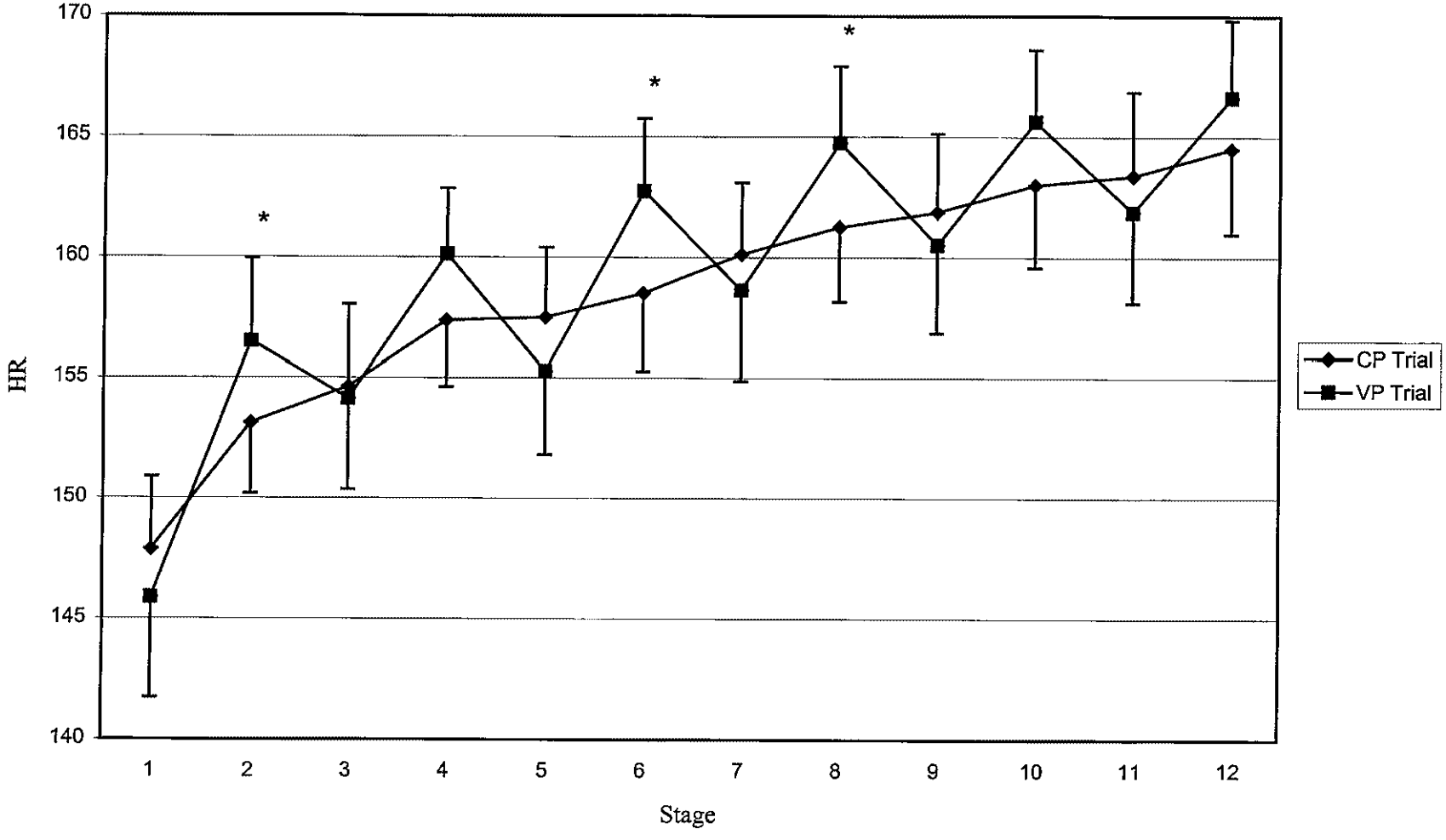


Figure 1c. HLa During CP and VP Trials.

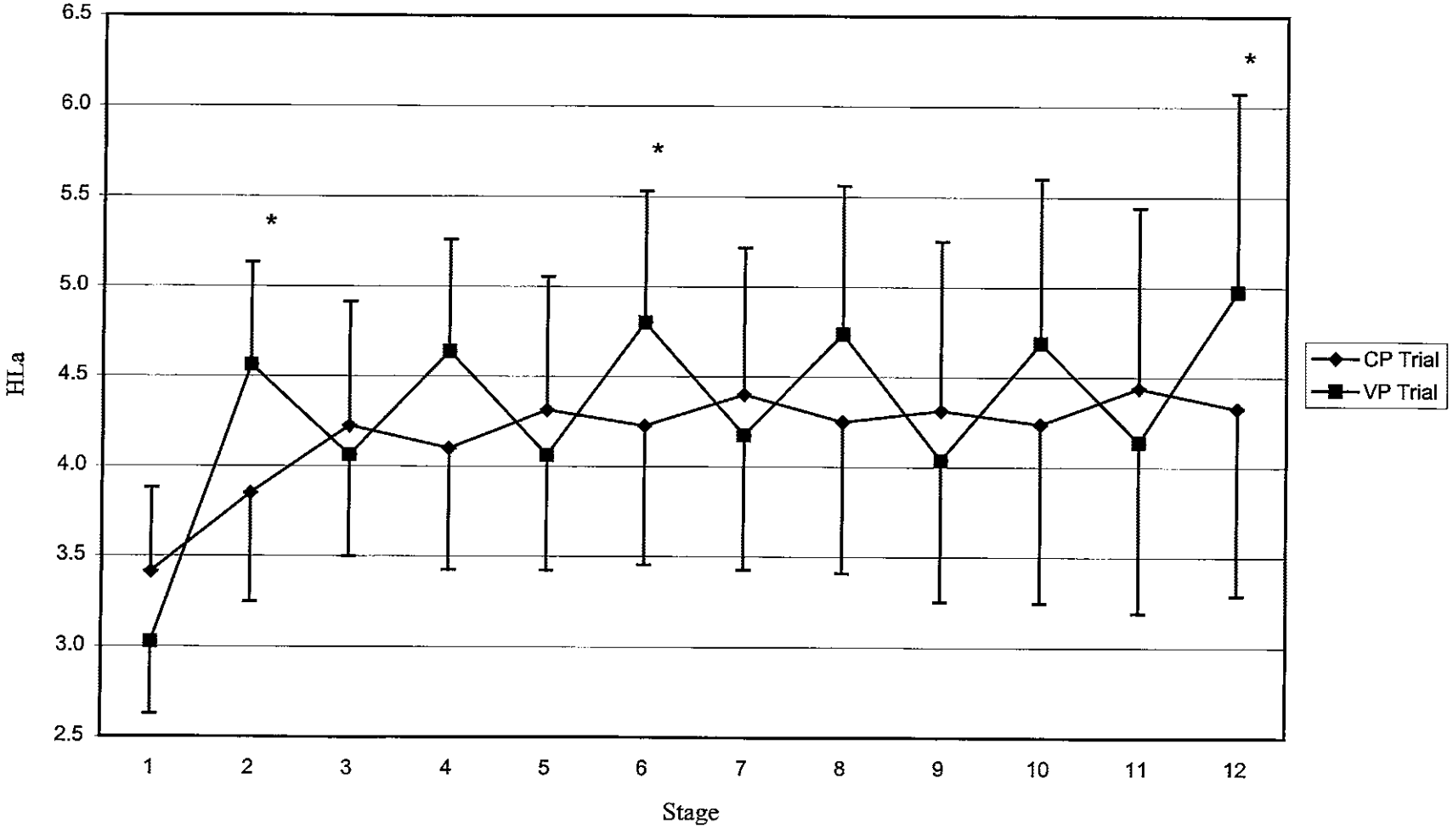
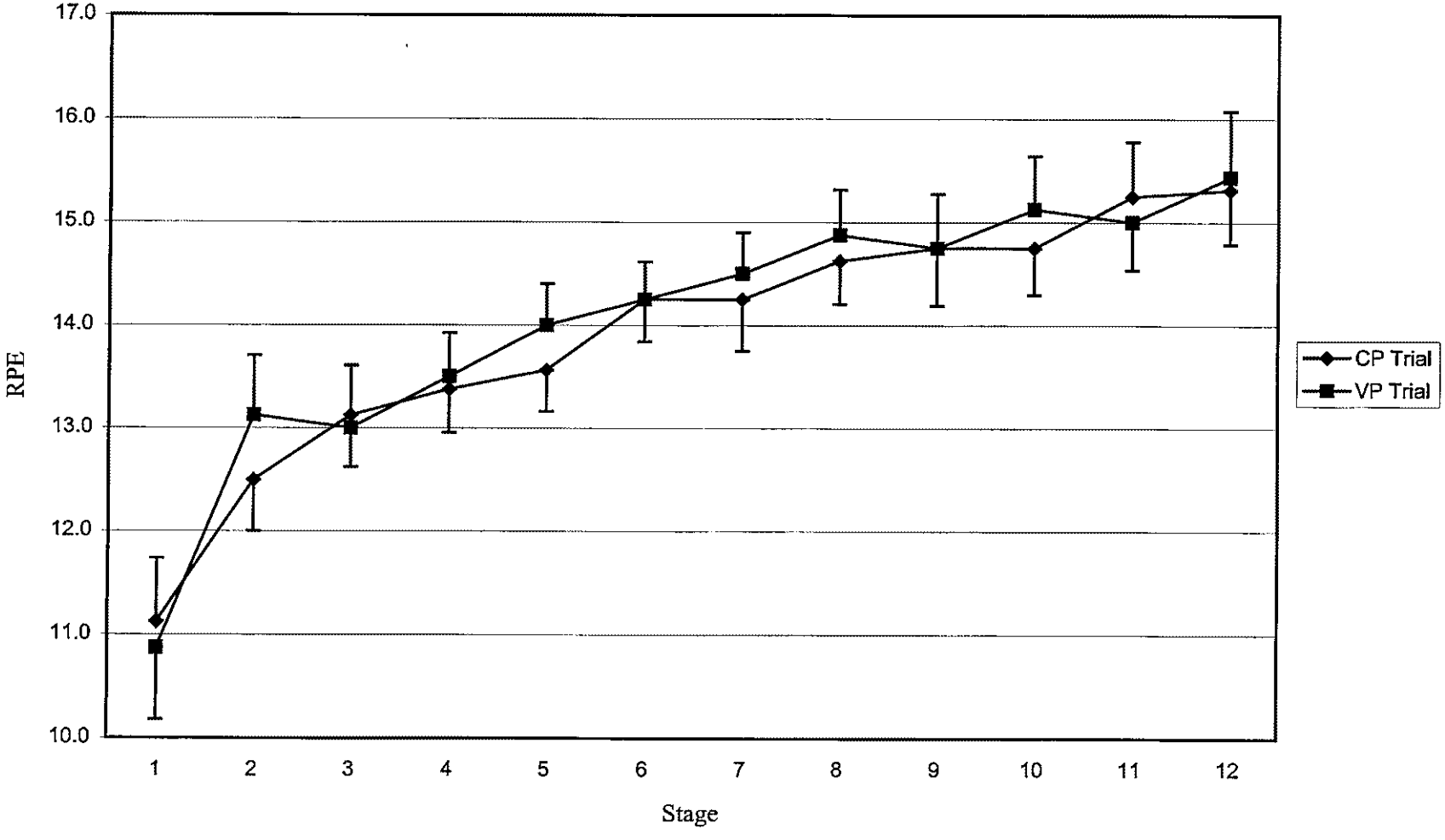


Figure 1d. RPE During CP and VP Trials.



REFERENCES

American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription.* 5th ed. Baltimore: Williams and Wilkins, 1995, p. 17-19, 292.

Åstrand, I., P. O. Åstrand, E. H. Christensen, and R. Hedman. Intermittent muscular work. *Acta Physiol. Scand.* 48: 448-453, 1960.

Borg, G. A. Psychophysical bases of perceived exertion. *Med. Sci. Sports Exerc.* 14: 377-381, 1982.

Christensen, E. H., R. Hedman, and B. Saltin. Intermittent and continuous running. *Acta Physiol. Scand.* 50: 269-287, 1960.

Coyle, E. F., A. R. Coggan, M. K. Hopper, and T. J. Walters. Determinants of endurance in well-trained cyclists. *J. Appl. Physiol.* 64: 2622-2630, 1988.

Coyle, E. F., M. E. Feltner, S. A. Kautz, M. T. Hamilton, S. J. Montain, A. M. Baylor, L. D. Abraham, and G. W. Petrek. Physiological and biomechanical factors associated with elite endurance cycling performance. *Med. Sci. Sports Exerc.* 23: 93-107, 1991.

De Groot, G., A. Sargeant, and J. Geysel. Air friction and rolling resistance during cycling. *Med. Sci. Sports Exerc.* 27: 1090-1095, 1995.

De Koning, J., G. de Groot, and G. J. van Ingen Schneau. Ice friction during speed skating. *J. Biomech.* 25: 565-572, 1992.

Di Prampero, P. E., G. Cortili, P. Mognoni, and F. Saibene. Equation of motion of a cyclist. *J. Appl. Physiol.: Respirat. Environ. Exercise Physiol.* 47: 201-206, 1979.

Foster, C., A. C. Snyder, N. N. Thompson, M. A. Green, M. Foley, and M. Schrager. Effect of pacing strategy on cycle time trial performance. *Med. Sci. Sports Exerc.* 25: 383-388, 1993.

Fox, E. L., S. Robinson, and D. L. Wiegman. Metabolic energy sources during continuous and interval running. *J. Appl. Physiol.* 27: 174-178, 1969.

Hagberg, J. M., J. P. Mullin, J. Bankre, and J. Limberg. Physiological profiles and selected psychological profiles of national-class American cyclists. *J. Sports Med.*

Phys. Fitness 19: 341-346, 1979.

Hagberg, J. M., J. P. Mullin, M. D. Giese, and E. Spitznagel. Effect of pedaling rate on submaximal exercise responses of competitive cyclists. *J. Appl. Physiol.* 51: 447-451, 1981.

Hawley, J. A. and T. D. Noakes. Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur. J. Appl. Physiol.* 65: 79-83, 1992.

Hermansen, L. and I. Stensvold. Production and removal of lactate during exercise in man. *Acta Physiol. Scand.* 86: 191-201, 1972.

Kyle, C. R. Reduction of wind resistance and power output of racing cyclists and runners travelling in groups. *Ergonomics* 22: 387-397, 1979.

Kyle, C. R. Selecting cycling equipment. In: *High-Tech Cycling*, edited by E. R. Burke. Champaign, IL: Human Kinetics, 1996, p. 1-44.

Loftin, M. and B. Warren. Comparison of a simulated 16.1-km time trial,V O_{2max} and related factors in cyclists with different ventilatory thresholds. *Int. J. Sports Med.* 15: 498-503, 1994.

Matheny, F. *Bicycling Magazine's Complete Guide to Riding and Racing Techniques.* Emmaus, PA: Rodale Press, 1989, p. 106, 112.

McCole, S. D., K. Claney. J.-C. Conte, R. Anderson, and J. M. Hagberg. Energy expenditure during bicycling. *J. Appl. Physiol.* 68: 748-753, 1990.

Miller, F. R. and T. G. Manfredi. Physiological and anthropometrical predictors of 15-kilometer time trial cycling performance time. *Res. Quart. Exerc. Sport* 58: 250-254, 1987.

Olds, T. S., K. I. Norton, and N. P. Craig. Mathematical model of cycling performance. *J. Appl. Physiol.* 75: 730-737, 1993.

Olds, T. S., K. I. Norton, E. L. A. Lowe, S. Olive, F. Reay, and S. Ly. Modeling road-cycling performance. *J. Appl. Physiol.* 78: 1596-1611, 1995.

Pollock, M. L., D. H. Schmidt, and A. S. Jackson. Measurement of cardiorespiratory fitness and body composition in the clinical setting. *Compr. Ther.* 6: 12-27, 1980.

Swain, D. P. Varying power to optimize cycling time trial performance on hills and in wind. *Med. Sci. Sports Exerc.* 29: 1104-8, 1997.

Whitt, F. R. A note on the estimation of the energy expenditure of sporting cyclists. *Ergonomics* 14: 419-424, 1971.