CRITICAL POWER AS A PREDICTOR OF PERFORMANCE IN A BICYCLE TIME TRIAL

THESIS

Presented to the Graduate Council of the University of North Texas in Partial Fulfillment of the Requirements For the Degree of

MASTER OF SCIENCE

By

Brian Dangelmaier, B.A.
Denton, TX
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Certain measures of aerobic power have been shown to have a high relationship with endurance performance. Critical power (CP) has also been shown to be well correlated to endurance performance, but few studies have evaluated its use in a competitive scenario. In this study, cardiorespiratory-metabolic measures were evaluated in 13 highly trained cyclists to determine their relationship to performance in a 17 km time trial. Critical power, determined from the nonlinear power-time model, was also evaluated to determine its relationship to performance in a 17 km time trial.

Results indicate that the traditional indicators of VO$_{2\text{max}}$ and ventilatory anaerobic threshold were well correlated to TT performance ($r=-0.86$, $r=-0.79$, respectively). The principal finding from this study was that performance in a bicycle time trial is related to CP at least as well as to cardiorespiratory-metabolic measures. In fact, the results from this study suggest that the relationship between performance and CP is stronger ($r=-0.89$). Use of the critical power concept is attractive because testing requires only a cycle ergometer and a stopwatch to estimate a parameter of aerobic fitness.
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Competitive cycling is a physiologically demanding sport. Bicycle races may range from a 200m sprint lasting approximately 10 seconds to the Tour de France of 23 days duration, covering approximately 5000 km. This vast range of competitive distances has resulted in cyclists specializing in events which place similar demands on the metabolic energy producing systems. Within this cornucopia of events, and placed within all multi-day stage races, is the individual time trial. Although distances and types of terrain vary somewhat, individual time trials are events that require cyclists to ride at their maximal sustainable velocity for the duration of the race without the benefit of riding within a pack of other riders and taking advantage of the subsequent reduced wind resistance. The recent history of bicycle races, such as the Tour de France, has illustrated the importance of the individual time trial. The overall winner repeatedly finishes in the top five, and often is the winner, in each time trial within the longer stage race.

Because of the apparent correlation between a cyclist's ability to perform in a time trial and success in their racing (Borysewicz, 1985), it seems desirous to
be able to determine factors related to, and/or predict, performance in such an event.

Several physiological parameters are used to describe the characteristics of competitive endurance athletes. Among the parameters often investigated are maximal oxygen uptake ($\text{VO}_{2\text{max}}$), anaerobic threshold (Farrell, Wilmore, Vodak, & Kurtz, 1979; Hagberg and Coyle, 1983).

Maximal oxygen uptake is an important determinant of an individual's ability to perform endurance exercise (Costill, 1967; Shephard, 1976). Elite cyclists typically possess a maximal oxygen uptakes in excess of 69 ml·kg$^{-1}$·min$^{-1}$ (Saltin, 1967; Stromme, 1977; Burke, 1980; Coyle, et al., 1991).

Anaerobic threshold (AT) represents a metabolic rate where the elimination of blood lactate from the blood is maximal and equal to the rate of diffusion of lactate from the exercising muscle to the blood (Stegmann & Kindermann, 1981). Stegmann and Kindermann also reported that well-trained athletes could exercise at their AT for 50 min. with individual steady-state blood lactate values varying from 2 to 7 mMol·l$^{-1}$. Anaerobic threshold is also identified using ventilatory criteria, such as a non-linear increase in minute ventilation ($V_e$) and a systematic increase in ventilatory equivalent for oxygen ($V_e/\text{VO}_2$) without any increase in ventilatory equivalent for carbon dioxide ($V_e/\text{VCO}_2$) (Wasserman, Whipp, Koyal, & Beaver, 1973; Davis, Vodak, P., Wilmore, Vodak, J., & Kurtz, 1976; Davis, Frank, Whipp, & Wasserman, 1979).
By measuring $V_{O_2\text{max}}$, ventilatory threshold, blood lactate concentrations, and other variables in highly trained cyclists, it is possible to determine the demands of cycling in various situations. Once measured, a work/performance profile may be made. Often coaches and selection committees use the results from these tests to determine training strategies and/or team selections.

Typically, the testing protocols require the use of complex, expensive equipment for respiratory gas analysis or blood analysis. These and other invasive testing protocols are often not practical in some laboratories or in the field.

A test that can validly estimate parameters of aerobic fitness without any invasive procedures or sophisticated expensive equipment would seem attractive for small laboratories, for field testing, or as a tool for coaches and athletes. Use of the critical power concept is attractive because testing requires only a cycle ergometer and a stopwatch to estimate a parameter of aerobic fitness. The critical power concept is based on a hyperbolic relationship between power output and time to exhaustion. In theory, the CP parameter provides an estimate of the maximal power that can be sustained “for a very long time without fatigue” (Monod & Scherrer 1965, p.329).

This investigation evaluated the use of the critical power concept as an indicator of aerobic fitness and as a predictor of performance in a time trial.
Statement of the Problem

The intent of this investigation was to determine if the critical power concept could be used to predict the performance of cyclists in a time trial.

Purpose of the Study

The purpose of this investigation was to evaluate the relationships between indicators of aerobic power (VO_{2max}, ventilatory threshold, CP) and observed performance in a bicycle time trial.

Hypothesis

A high relationship will be found between critical power and observed performance in a bicycle time trial thereby allowing the use of critical power as a predictor of performance in a bicycle time trial.

Delimitations

Listed below are the factors incorporated in this study by the investigator as a means of delimiting this investigation to increase the feasibility and help insure meaningful results.

1. Subjects used in this study included only licensed racers from the United States Cycling Federation who were actively training and racing.
2. Subjects performed two separate time trials, each on a different day, under similar conditions, to evaluate test-retest reliability of the results.

3. Subjects performed each time trial using only their regular road racing bicycle without the use of any aerodynamic equipment.

4. Testing was completed within a two week period to reduce any training effect possibly caused by the continued training of the subjects.

Limitations

Listed below are several factors that could potentially act as negative aspects and confound results of the this investigation.

1. Conclusions based on the results from this study were made under the assumption that the subjects performed maximal efforts during each test.

2. An assumption was made that each of the subjects participating in this study were of approximately similar frontal areas and that their relative positions on their bicycles during the time trials were similar so that the effect of wind resistance was similar on each of them.

3. It is not known if the results obtained from this investigation, using only category II and III cyclists, can be generalized to apply to all cyclists.

4. It is not known if the results obtained from this investigation to predict performance in a 17 km time trial can be generalized to other longer or shorter time trial distances.
CHAPTER 2

RELATED LITERATURE

Factors Related to Performance

Maximal oxygen uptake has long been recognized as an important determinant of endurance performance (Åstrand & Rodahl, 1977), generally because it sets the upper limit for steady-state oxygen consumption and for anaerobic threshold, the point at which lactate begins to accumulate in the blood (Farrell et al., 1979; Hagberg & Coyle, 1983). It is well known that athletic performance during endurance events (i.e., lasting from ~10 min. to several hours) is determined by the highest steady-state rate of O$_2$ consumption that can be tolerated and by the biomechanical economy of the movement (Farrell et al., 1979; Hagberg & Coyle, 1983).

Coyle et al. (1988) investigated the determinants of endurance in well-trained cyclists. Aerobic parameters including maximal oxygen uptake and blood lactate threshold were measured. Results indicated the best predictor of performance time to fatigue was \%VO$_{2\text{max}}$ at lactate threshold (r=0.90; p<0.001). Data were obtained in the laboratory using a cycle ergometer. These investigators suggested that future research should focus on how these type of results might relate to actual competitive cycling performance (i.e., time trial).
Critical Power Concept

The relationship between power output and time to exhaustion during cycling exercise can be approximated by a hyperbolic function (Monod & Scherrer 1965; Moritani et al., 1981; Poole, Ward, Gardner, & Whipp, 1988; Poole, Ward, Whipp, 1990; Overend, Cunningham, & Patterson, 1992; Jenkins & Quigley, 1990, 1991; Gaesser, Carnevale, Garfinkel, & Walter, 1990; Housh, D., Housh, T., & Bauge, 1989). Theoretically, this relationship can be used to derive a parameter which represents the maximal sustainable power, or CP, that can be sustained without fatigue.

This relationship may be presented in three mathematically equivalent forms. In the nonlinear power-time model, CP is the power asymptote; in the linear work-time model, CP is the slope of the work-time relationship; and in the linear power-1/time model, it is the y-intercept. Figure 1 presents the critical power nonlinear power-time model.
Figure 1. Critical Power -- Nonlinear Power-Time Model
Validity of Critical Power

The concept of critical power was first reported by Monod and Scherrer (1965). They investigated the relationship between power output and time to exhaustion during multiple bouts of exercise on specific, isolated muscle groups. They derived a linear relationship between total work performed and time to exhaustion from the hyperbolic relationship between power output and time to exhaustion. Monod and Scherrer defined critical power as the slope of the regression of work on time, and identified CP as the maximum work rate that can be maintained "for a very long time without fatigue" (Monod & Scherrer, 1965, p. 329). Further, they suggested that "when the imposed power is inferior or equal to the critical power, it is evident...that exhaustion cannot occur" (Monod & Scherrer, 1965, p. 332).

Monod and Scherrer had subjects perform 4 or 5 exercise bouts for 2 to 24 minutes for use as predicting trials. From these exercise bouts, they derived the parameters of the work - time relationship. Monod and Scherrer concluded that CP could give a better understanding of the duration of a given activity at a particular work rate for a given muscle or muscle group.

Moritani, Nagata, DeVries, & Muro (1981) extended the use of the critical power concept to exercise on a bicycle ergometer. Values for the CP parameter were derived from three cycle ergometer tests by recording the subjects' total work performed in exhaustive exercise (or time limit at which the power output...
level could no longer be maintained) (i.e. a drop in pedaling frequency below 60 revolutions per minute (r.p.m.)). Their results indicated a high correlation ($r=0.928, p<0.01$) between CP and ventilatory anaerobic threshold (as seen by a nonlinear increase in $V_e$ and a systematic increase in $V_e/VO_2$ without any increase in $V_e/VCO_2$). Moritani et al. concluded that it was possible to calculate the maximal sustainable level of power output, and that it theoretically could be maintained indefinitely.

Further evidence of the use of CP in cycle ergometry as an indicator of aerobic power can been seen from the study of Gaesser and Wilson (1988). They reported, based on results from multiple predicting trials, that CP represents maximal sustainable power and represents “an inherent characteristic of the aerobic energy supply system” (Gaesser and Wilson, 1988, p.419).

Reliability of Critical Power

Investigators have evaluated the reliability of parameter estimates derived from two sets of predicting trials (Gaesser & Wilson, 1988; Nebelsick-Gullett, Housh, Johnson, & Baugh, 1988; Smith & Hill, 1993). Gaesser and Wilson (1988) had 11 male subjects perform two sets of five predicting trials, each trial performed on a separate day with less than a week separating the first and second series. They reported test-retest correlation for CP of 0.96.
Nebelsick-Gullett et al. (1988) also assessed the reliability of the CP estimates. They had 25 female subjects perform two sets of three predicting trials. In this investigation, each set of trials were performed in a single day with at least 30 minutes recovery between trials. The second set of trials was then performed one to seven days later. They reported a test-retest correlation of 0.94 for CP.

Smith and Hill (1993) assessed the stability of the CP parameter in 13 men and 13 women from across the results of five predicting trials. They reported a test-retest correlation of 0.92 for CP. The results from these three investigations suggest that the critical power estimates are quite reliable. In all three cases, the test-retest correlations were all greater than 0.90.

Summary

A review of the literature reveals several points. First, athletes competing in endurance sports such as competitive cycling require a high degree of aerobic fitness to be successful. Traditional indicators of aerobic fitness are maximal oxygen uptake ($VO_{2\text{max}}$) and anaerobic threshold. Although valid as indicators of aerobic fitness, they require complex, expensive equipment to measure and the techniques are invasive.

Secondly, the use of CP provides a valid indicator aerobic fitness. This is seen in its high relationships to both traditional indicators of aerobic fitness, maximal oxygen uptake ($VO_{2\text{max}}$) and individual anaerobic threshold. It has also
been shown to be a reliable measure. Additionally, the use of the critical power concept is attractive because testing requires only a cycle ergometer and a stopwatch to estimate a parameter of aerobic fitness.
CHAPTER 3

METHODS

Subjects

Subjects for this investigation were recruited from local bicycle racing clubs. Each subject was licensed to race by the United States Cycling Federation (USCF), the national governing body of bicycle racing in the United States. Subjects were nine men and four women. The women were of mean (±SD) age 32 yr ± 3, height 168 cm ± 7.5, and mass 63 kg ± 1.2. The men were age 31 yr ± 4, height 180.5 cm ± 6.2, and mass 77.5 kg ± 3.2. All subjects were screened to meet American College of Sports Medicine guidelines for whom a medical exam and physician supervised exercise test were not required. All subjects provided written informed consent prior to data collection. The methods for this investigation were previously approved by the University Institutional Review Board.

Overview

Data collection for this investigation was completed both in the laboratory and in the field. For the laboratory testing, subjects reported to the laboratory a total of six times. After screening, subjects' VO$_{2\text{max}}$ and ventilatory anaerobic threshold were measured. Further laboratory testing consisted of constant
power tests to determine the CP parameter. Field testing consisted of performance of two all-out 17 km bicycle time trials on an out and back course. Statistical analyses included correlations between the subjects’ mean 17 km time and the laboratory measures (CP, ventilatory anaerobic threshold, and VO$_{2\text{max}}$).

**Screening**

During the initial visit, subjects were screened and familiarized with procedures for both the laboratory and field testing. Each subjects’ height and weight were measured. Each bicycle that was to be used by the subjects for the field testing was measured for seat and top tube lengths, handlebar height, and the fore-aft position of the seat. Each of these measurements were recorded for future use during the laboratory testing. Informed consent was also obtained.

**VO$_{2\text{max}}$ and Ventilatory Anaerobic Threshold**

For VO$_{2\text{max}}$ testing, each subject performed the test on an electronically-braked Ergoline cycle ergometer (SensorMedics, Anaheim, CA, USA) which provides a constant power independent of pedal rate. The ergometer was modified by the installation of dropped, racing style handlebars and a racing saddle, both similar to those typically used by the subjects on their racing bicycles. The ergometer was also fitted with the subjects’ own pedals. In all cases these pedals were designed to accept a clipless pedal system as used by each subject. The ergometer was adjusted to measurements of each subjects’
racing bicycles. All of these modifications were made so that the ergometer was 
as similar as possible to each subject's own racing bicycle (Coyle et al., 1988).

During the \( \text{VO}_{2\text{max}} \) test, after a five minute warm-up at a workrate of 125 W, 
the work rate was increased by 25 W every minute until volitional exhaustion 
ocurred (Hopkins & McKenzie, 1994). Pedal cadence was at the subjects’ 
discretion, since work rate was independent of pedal cadence. However, the 
cadence chosen by all subjects was approximately 90 r.p.m. Each subject was 
fit with a low resistance breathing valve attached to a pneumotach. Expired 
gases were collected and analyzed using a MedGraphics CPX metabolic cart 
(St. Paul, MN, USA). The determination of \( \text{VO}_{2\text{max}} \) was made using gas 
exchange parameters, i.e. a plateau in oxygen consumption between 
progressive work loads and a respiratory exchange ratio of 1.1 or greater.

The determination of ventilatory anaerobic threshold was made during the 
\( \text{VO}_{2\text{max}} \) test using gas exchange parameters, such as a nonlinear increase in \( \text{V}_\text{E} \) 
and \( \text{VCO}_2 \) and a systematic increase in \( \text{V}_\text{E}/\text{VO}_2 \) without any increase in \( \text{V}_\text{E}/\text{VCO}_2 \) 
(Wasserman et al. 1973; Davis et al. 1976,1979). Three independent 
investigators, experienced with ventilatory threshold determinations, estimated 
the inflection points. Final decisions were based on consensus among all three 
investigators.
Critical Power

Further lab testing consisted of a series of constant power tests to estimate the CP parameter. Each subject performed a learning trial prior to testing to reduce the learning effect reported by other investigators (Gaesser & Wilson 1988; Smith & Hill 1993). The power output for the learning trial was individually assigned, based upon the power outputs completed during the VO\textsubscript{2max} test. In each case, the power output selected was equal to the highest power output sustained for at least 30 seconds during the VO\textsubscript{2max} test.

Subjects performed four all-out constant power tests, each on a separate day, on the same electronically braked ergometer used for the VO\textsubscript{2max} testing. For each test, subjects warmed up for five minutes at a submaximal power output (135 W of the women and 150 W for the men). After the warm-up, subjects rested for three minutes (Smith & Hill, 1993). Pre-selected power outputs were calculated to elicit exhaustion ranging from one to ten minutes (Poole, 1986; Hill, 1993). Subjects then accelerated against zero resistance until they reached 100 r.p.m. The work rate was then imposed (full effect within 1 to 3 s) and timing began. Pedal cadence was again at the subjects' discretion, since work rate was independent of pedal cadence. The test was terminated when subjects could not maintain the power output, as judged by the inability to sustain 50 r.p.m. despite strong verbal encouragement. Subjects were not
aware of their elapsed time during any of the tests, nor the results of any trial until all trials had been completed.

Data from the four constant power test were used to calculate each subjects' CP using SAS statistical software. The relationship between power and time to exhaustion was mathematically described by nonlinear regression of time with power, with power as the dependent variable. This iterative regression analysis fits values for the variables of power (P) and time (t) to a hyperbolic function in the form \( t = \frac{AWC}{P-CP} \). AWC is anaerobic work capacity and represents the anaerobic nature of the parameter. In the nonlinear model, AWC is the degree of curvature in the hyperbolic relationship. For this investigation, the AWC parameter was not under evaluation.

Time Trials

Field testing consisted of two individual time trials on a 17 km out and back road course. Time trials were held on separate days under similar atmospheric conditions. Subjects rode their standard road racing bicycles, absent of any aerodynamic equipment, for both tests. Subjects started each test in random order at 30 s intervals, and their total elapsed time was calculated. This protocol is similar to that used in all USCF sanctioned time trial events. The faster of the two time trial times was used for statistical analyses.

Correlations between the performance measure (time for the 17 km time trial) and the laboratory measures (CP, ventilatory threshold, and \( VO_{2\text{max}} \)) were
calculated. Reliability of the time trial performance was assessed by calculating the correlation between the times for the first and second trials.
CHAPTER FOUR

RESULTS

Individual physiological data are presented in Table 1. Average VO$_{2\text{max}}$ values for the subjects was 4596 ± 799 ml·min$^{-1}$. The results of the time trial and of the laboratory measures are presented in Table 2. The 13 subjects completed the 17 km time trial in an average time of 26.6 ± 1.1 min at an average speed of 39.2 km·h$^{-1}$. Correlation between the times for the two time trials was 0.92. The faster of the two time trials was used for statistical analyses. Subjects' average CP was 299 ± 61 W. Subjects' average power output at ventilatory threshold (VT$_{\text{vent}}$) was 290 ± 67 W, and average oxygen uptake at ventilatory threshold (VT$_{\text{VO2}}$) was 3615 ± 750 ml·min$^{-1}$.

The relationships between VO$_{2\text{max}}$, CP, VT$_{\text{vent}}$, VT$_{\text{VO2}}$ were determined. There were significant correlations between time in the 17 km time trial (TT) and CP ($r=-0.89$, $p<.001$), VT$_{\text{vent}}$ ($r=-0.80$, $p<.001$), VT$_{\text{VO2}}$ ($r=-0.79$, $p<.001$), and VO$_{2\text{max}}$ ($r=-.86$, $p<.001$). These relationships are graphically presented in Figures 2-5.
### Table 1. Subject Descriptive Data

<table>
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<tr>
<th>Subject</th>
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### Table 2. Performance Measures

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<th>VTwatt (W)</th>
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Figure 2. Correlation of TT Performance to CP

Figure 3. Correlation of TT Performance to VT watts
Figure 4. Correlation of TT Performance to VO2max

Figure 5. Correlation of TT Performance to VTvo2
CHAPTER FIVE

DISCUSSION

The purpose of this study was to evaluate the relationships between indicators of aerobic capacity and performance in a time trial. Results indicated that the traditional indicators, $V_0^{max}$ and VT, were well correlated to TT performance ($r=-0.86$, -0.79, $p<.001$, respectively). These findings are similar to those of several studies using both cycling (Burke, 1980; Burke, Cerny, Costill, & Fink, 1977; Hagberg, Mullin, Bahrke, & Limburg, 1979) and running (Costill, Thomason, & Roberts, 1973; Foster, Costill, Daniels, & Fink, 1978; Morgan, Baldini, Martin, & Kohrt, 1989) protocols. In general, the aerobic power displayed by the subjects in the present study was well within the range reported for other highly trained or elite endurance athletes.

The principal finding from this study was that performance in a bicycle time trial is related to CP at least as well as it is to the traditional measures of aerobic power. In fact, the results from this study suggest that the relationship between performance and CP appears stronger than the relationship between performance and $V_0^{max}$ and VT. As previously noted (Hill, 1993), an advantage of CP over cardiorespiratory-metabolic measures is that CP can be obtained without the need for expensive equipment for gas analysis, without the need for
invasive techniques to measure blood lactate, and without the need for subjective assessments for determination of lactate or ventilatory thresholds.

There are few studies that have attempted to relate laboratory measures to actual cycling performance in homogeneous sample populations of highly trained or elite cyclists. Hopkins & McKenzie (1994) reported that power output (W) at VT highly related \( r=-0.81 \) to performance in a 40 km time trial. Their finding would seem to support the finding of the present study, since CP has a high relationship to VT (Moritani et al., 1981).

Coyle et al. (1991) reported that there was a correlation of 0.88 between mean power output (W) in a 60-min laboratory cycling test and personal best performance in a 40 km time trial. Also found were correlations between performance and work rate (W) at the lactate threshold \( r=-0.54 \), \( \text{VO}_2 \) at the lactate threshold \( r=-0.59 \), and \( \text{VO}_{2\text{max}} \) \( r=-0.43 \). As in the present study, the laboratory power measure was more slightly more strongly related to the criterion performance measure than were the cardiorespiratory-metabolic measures.

Determination of CP by means of performance of a series of short all-out tests is certainly easier and more practical for subjects and investigators than the performance of a 60 min all-out test. Further, the reliability of the CP parameter has been described in the literature (Smith & Hill, 1993), but long trials to exhaustion may not be reliable (Poole et al., 1988; Gaesser & Wilson, 1988).
While it can not be said conclusively that CP performance is the best predictor of performance of a bicycle time trial, it has been shown from this study and others that CP is a valid indicator of sustainable aerobic power. Aerobic power in itself is known to have a high relationship with endurance performance. Given that CP is related to indicators of aerobic power such as $VO_{2\text{max}}$ and VT, and with the results from this study showing a high relationship to performance in a 17 km time trial, it can be concluded that CP can be used as a predictor of time trial performance. Clearly, there are variables that were not considered in this investigation that may play a role in determining performance on a bicycle. Factors such as aerodynamic positioning, efficiency of the rider, and rider motivation may play an important role. Results clearly indicate that CP, which is simple to determine, is strongly related to measures of aerobic power, can be used as a predictor of performance even in a homogeneous sample.
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