University of Alberta

A Comparison of Critical Velocity Estimates to Actual Velocities in Predicting Simulated Rowing Performance

by

Michael Kennedy ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment of the requirements for the degree of Masters of Science

Faculty of Physical Education and Recreation

Edmonton, Alberta
Fall 1997

0-612-22611-5

ABSTRACT

The Critical Velocity (CV) concept was applied to simulated rowing to determine the most accurate CV for the prediction of 2000 metre velocity; the best predictor of 2000 metre velocity; and, the effect of model and distance on the CV estimate. Six randomized maximal exertion trials on separate days were followed by a simulated 2000 m race on a Concept II model C rowing machine. Three mathematical models were applied to 4 distance combinations resulting in 12 different CV estimates. The analyses showed that the type of model influenced the CV estimate, and longer distances were the more stable estimate regardless of model. The closest prediction of actual 2000 m velocity was provided by using all 6 distances combined with the linear distance/time model. It was concluded that the prediction of actual 2000 m velocity was most accurate with a nonlinear model and medium to long distance sets.

ACKNOWLEDGEMENTS

Dr. Gordon Bell, for his academic and communication skills which I admire

Dr. Yagesh Bhambhani

Dr. Judy Cameron

My Mother, who never cared how I finished as long as I did my best

Dr. Michael Kennedy, always an inspiration

My Family

The Rowers, for their dedication and effort

Julie, best of friends!

TABLE OF CONTENTS

LIST OF TABLES

PAGE

Chapter 3

Chapter 4

LIST OF FIGURES

PAGE

Chapter 3

LIST OF SYMBOLS, NOMENCLATURE OR ABBREVIATIONS

AD	All Distance
ATP	Adenosine Triphosphate
AWC	Anaerobic Work Capacity
CP	Critical Power
CV	Critical Velocity
IAT	Individual Anaerobic Threshold
L	Long Distance
M	Medium Distance
M1	Model One
M2	Model Two
M3	Model Three
MLSS	Maximal Lactate Steady State
PCr	Phosphocreatine
OBLA	Onset Of Blood Lactate Accumulation
S	Short Distance
tLim	Time Limit At Set Workload
$\dot{V}O_2$	Oxygen Consumption Per Minute
$\dot{V}O_2$ max	Maximal Oxygen Consumption
VT1	Ventilatory Threshold One
VT2	Ventilatory Threshold Two
vVmax	Velocity At Maximal Oxygen Consumption
wLim	Maximum Work Done At Set Workload

CHAPTER 1

INTRODUCTION

Background:

Monod and Scherrer (1965), proposed that an individual possesses a "critical" power output in muscular contractions and " when the imposed power is inferior or equal to the critical power, exhaustion cannot occur." Thus critical power (CP) is defined as the asymptote for the relationship of power output and time and is equal to an intensity where fatigue does not impede muscular work (Monod & Scherrer, 1965). Maintenance of CP may be regulated by the availability of the predominate substrate used during the performance. If the load or resistance was great enough to predominately utilize high energy, intramuscular phosphagens, the CP value will be regulated by the availability of ATP and PCr in the muscle. If CP was determined for loads which incur an aerobic response to the imposed trial loads then maintenance of CP would be primarily limited by the availability of glycogen and/or accumulation of fatigue related metabolic by products. Therefore, CP can be both intensity dependent and substrate or metabolically dependent.

The field of CP research stems from this original premise and has many applications in a variety of different performance environments. One of the applications developed from CP research was Critical Velocity (CV). Critical Velocity can be distinguished from CP by the substitution of velocity for power output therefore using velocity as the criterion measure. Critical Velocity can be defined as the maintenance of a maximal average velocity over a given distance or time. Wakayoshi, Ikuta, et al. (1992) extended this definition by implying that CV was an intensity that can be maintained for a very long time without exhaustion. Critical Velocity research has primarily focused on sports where body weight is non-supported (i.e. running) or semi-supported (i.e. swimming). At present, no published research has been done involving CV and a fully weight supported sport such as rowing.

Maximal oxygen consumption ($\dot{V}O_2$ max) testing, a gold standard of aerobic fitness, has only been used as an inference of performance (Hermansen & Saltin, 1969). Rowers are known to have high $\dot{V}O_2$ max scores (Secher, 1993) yet the ability to assess aerobic power and its relationship to rowing performance has been limited. Critical Velocity parameter estimates formed through maximal exertion tests of short duration may provide a more valid indicator of rowing performance than $\dot{V}O_2$ max. The assessment of rowing performance using CV parameter estimates may benefit rowers a number of ways: rowers are able to monitor aerobic fitness in a field setting (ie. if CV increases / decreases inferences can be made about aerobic fitness); CV may be a good predictor of actual performance (Wakayoshi, Ikuta, et al. 1992), and CV may be used as a tool for quantifying intensity (Moritani, Nagata, deVries, & Muro, 1981).

Critical Velocity estimates are based on maximal exertion trials and have been shown to predict performance over a given race distance (Kranenburg & Smith, 1994; McDermott, Forbes, & Hill, 1993). However, the accuracy of CV as a predictor of performance has been questioned by a number of researchers (Hill, 1993; Pepper, Housh, & Johnson, 1992), who report that CV has a tendency to overestimate performance. The validity of CV could be questioned by such results but it seems that methodological error such as trial duration and or the appropriateness of the mathematical model used would contribute to the over prediction in CV, not the concept itself. Critical Velocity theory has unique values for each sport and inferences can only be drawn in the performance environment that the CV parameters were developed.

The sport of rowing uses a 2000 metre time trial on a stationary rowing machine as an established off the water mark of performance and has also been developed as an international event (Concept II Ergo Update, 1995). In rowing, it has been used to aid in athlete selection, boat seat selection and to monitor training. The use of pacing strategies for this 2000 metre indoor event would aid the rower in achieving the maximal average rowing velocity to produce the fastest time. Determining CV for the 2000 metre rowing performance race could be used as a tool to create a critical pace for each individual. Therefore validation of CV as an accurate predictor of actual average velocity over 2000 metres is important. Most researchers have used a minimum of three, short (less than 50% of the predicted distance) maximal exertion performance trials (Clingeleffer, McNaughton, and Davoren, 1994) to produce their CV estimate. The convention of performing trials less than half of the predictive distance may contribute to the inaccuracies seen in CV research. The 2000 metre race has been shown to be an event relying primarily on the aerobic energy system to supply the majority of ATP energy for the distance. Therefore longer trials (ranging above and below 1000 metres) which have a greater contribution from the aerobic energy system should be used.

The other major determining factor in accurate prediction of CV has been the mathematical model used. The three mathematical models most widely used in research investigations are, a nonlinear model and two linear models. The non linear model utilizes the variables velocity (y axis) and time (x axis). The linear models are similar and both utilize a time component on the x axis (model 1 utilizes time as whole number, model 2 has time as a fraction (1/time)). As well, model 1 has a distance variable versus model 2 which utilizes a velocity unit on the y axis. In a performance setting, the mathematical model serves two purposes: to calculate values for the relationship between the performance and physiological parameters and, more importantly, to predict velocity over the selected race distance. Presently, there is no research which has compared the accuracy of different mathematical models in combination with different length trial sets to predict velocity over 2000 m in rowing.

Statement Of The Problem:

There is no CV model at this time that accurately predicts simulated rowing performance over 2000 metres.

Question 1:

Do the three mathematical CV models produce statistically different values (i.e. utilizing all six trials)?

Question 2:

Nine different CV values were generated from 3 sets of trial lengths (200,400,600, 800 {short}; 400, 600, 800, 1000 {medium}; 600, 800, 1000, 1200 {long}) each used in 3 different mathematical models (linear distance-time, linear velocity-1/time, and nonlinear velocity-time) to answer the following questions:

a) What are the main and interaction effects for mathematical models and length of trials?

b) Which CV estimates are statistically not different from actual velocity over 2000 m?

Question 3:

What is the relationship among 2000 metre velocity, maximal oxygen consumption and the most accurate Critical Velocity value (determined by no statistical difference between Critical Velocity and 2000 metre velocity)?

Research Hypotheses:

It was hypothesized that:

Hypotheses 1:

All CV models will produce statistically different values for Critical Velocity.

Hypotheses 2:

a) A significant interaction effect will be seen as well as a main effect for both model and length of trials.

b) The critical velocity parameter estimate created from the long combination of trials (600, 800, 1000 and 1200 metres) and the linear velocity -1/time model will most accurately predict actual performance velocity during a 2000 metre simulated rowing race.

Hypotheses 3:

Maximal oxygen consumption will account for most of the variability in prediction of 2000 metre velocity.

Justification:

The efficacy of CV research lies in the absence of tools for estimating, analysing and predicting performance. Presently the use of heart rate monitors, anaerobic threshold and $\dot{V}O_2$ max testing are the most popular means of analysing fitness, predicting performance, and prescribing training. All are only inferences of true performance, for example having the highest $\dot{V}O_2$ max does not necessarily suggest that the best performance will occur. Critical Velocity can be estimated from short duration maximal exertion performance trials and may provide a more accurate indication of predicted performance over a given distance.

Assumptions:

a) All subjects performed all of the trials with maximal physical and mental best efforts.

b) Fitness levels of the subjects did not change over the six weeks data was collected.

c) External stressors such as exams and sickness did not contribute to intra subject variability.

d) Physical activity prior to the trial on that day did not influence performance.

e) Time of day did not play a role in performances.

f) Hydration and energy stores were similar throughout the study for each subject.

g) Biomechanics of the rowing stroke did not influence the performance of each subject over the different trial lengths (i.e. a subject did not change his stroke pattern due to fatigue regardless of the trial length).

Limitations:

a) Three out of a possible five mathematical models were used to create the CV estimates.

b) The results may only be applied to simulated rowing not open water rowing.

REFERENCES

Clingeleffer, A., McNaughton, L. R., & Davoren, B. (1994). Critical power may be determined from two tests in elite kayakers. European Journal of Applied Physiology and Occupational Physiology, 68, 36-40.

Concept II ergo update. (1995, Spring). Copy Editor, 23, 1-15.

Hermansen, L., Saltin, B. (1969). Oxygen uptake during maximal treadmill and bicycle exercise. Journal of Applied Physiology, 26, 31-37.

Hill, D. W. (1993). The critical power concept a review. Sports Medicine, 16 (4), 237-254.

Kranenburg, K., & Smith, D. J. (1994). Prediction of 9.8 km performance in elite runners using critical speed (Abstract). Canadian Journal of Applied Physiology ,19, 24P.

McDermott, K. S., Forbes, M. R., & Hill, D. W. (1993). Application of the critical power concept to outdoor running (Abstract). Medicine and Science in Sports and Exercise, 25 (5), 610.

Monod, H., & Scherrer, J. (1965). The work capacity of synergic muscle groups. Ergonomics, 8, 329-338.

Moritani, T. A., Nagata, H. A., deVries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24, 339-350.

Pepper, M. L., Housh, T. J., & Johnson, G. O. (1992). The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. International Journal of Sports Medicine, 13 (2), 121-124.

Secher, N. (1993). Physiological and biomechanical aspects of rowing: Implications for training. Sports Medicine, 15, 24-42.

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

CHAPTER 2

REVIEW OF LITERATURE

Critical Power:

Initial Research:

The initial research involving Critical Power concepts utilized synergistic muscle groups in the leg. Monod & Scherrer (1965) found that when the imposed resistance was equal to the power asymptote of the hyperbolic relationship between power output and time, fatigue could not occur. Moritani, Nagata, deVries, & Muro (1981) applied the initial concept put forth by Monod et al. (1965), using cycle ergometry to correlate ventilatory threshold to CP in an attempt to provide evidence of the metabolic nature of CP. Nagata (1981) used positive change in Electromyographic (EMG) tracings as a marker of muscular fatigue in the quadriceps. Increased voltage-time ratio correlated significantly to changes in the EMG tracings during cycle exercise. DeVries, Moritani, Nagata, & Magnussen (1982) also showed that cycling at 4 supra maximal power outputs to fatigue created positive changes in the EMG tracings. Each work load had a distinct voltage-time value and when plotted gave R^2 of 0.9 - 0.99. The y-intercept of this relationship was CP (corresponded to no significant changes in EMG activity in the exercising muscle). Correlations between CP and both fatigue threshold (significant change in EMG tracings) and anaerobic threshold (increase in $\dot{V}e / \dot{V}O_2$ with no systematic increase in $\dot{V}e / \dot{V}CO_2$) were found to be $r = 0.87$ ($p<0.01$) (DeVries, Moritani, et al.). DeVries et al. (1987) created a test to measure Physical Work Capacity at Fatigue Threshold (PWCft) utilizing EMG tracings on exercising quadriceps muscles. By cycling at different submaximal trials, one of the work loads was found to have a voltage time relationship with a positive slope. This workload was deemed the PWCft and had a test-retest reliability coefficient of $r = 0.94$ ($p < 0.05$). A significant difference in work loads was found between Onset of Blood Lactate Accumulation (OBLA) and PWCft ($p < 0.05$). CP determined from two different trials (linear Wlim - Tlim model) and PWCft had a correlation of $r = 0.67$ ($p<0.05$) (DeVries, Tichy et al., 1987). It was reported that mean power outputs for PWCft and CP were not significantly different. Actual mean power outputs were not published so no comparison of the difference in actual power outputs can be made.

Critical Power Validation:

A recent review article (Hill, 1993) examined current concepts in CP research. Conclusions that CP was an effective tool for prediction and an inference of aerobic power must be interpreted cautiously. Hill stated that most error in CP testing was due to the number of trials used and the mathematical model chosen. Much CP research has involved validation of the parameter to other known physiological and physical values. A series of abstracts on CP validity found that CP was highly correlated to both maximal power output ($r = 0.91$, $p < 0.01$) and $\dot{V}O_2$max ($r = 0.84$, $p < 0.01$) (Talbert, Smith, & Hill, 1991); was subject to a learning effect between trials (trial 2 mean power output > than trial 1 by 10 watts) (Smith & Hill, 1993; Smith, Hill, & Talbert, 1991) and was a reasonable estimate of maximal sustainable power output which could be maintained for 90 minutes (Scarborough, Smith, Talbert, & Hill, 1991). Smith & Hill (1993) also found evidence of a gender bias in both the initial and secondary trials for determination of CP. The males had significantly different correlations than females ($r = 0.9$ [trial #1]; 0.92 [trial#2] for males and $r = 0.64$ [trial #1]; 0.8 [trial#2] for females, $p > 0.001$). As well, an age bias has been reported in regards to the physiological responses at CP when comparing young (mean age = 24.5 years) to elderly men (mean age = 70.7 years) (Overend, Cunningham, Paterson, & Smith, 1992). It was shown in young men that ventilation, blood lactate, and arterial carbon dioxide continued to change over 24 minutes of cycling at CP, but these parameters were stable in the elderly group (Overend et al.). The elderly group also had a CP approximately 5 % higher than the younger group when expressed as a percentage of maximal power output (Overend et al.).

The importance of Housh, Housh, & Bauge's (1989) work underlies the major criticism that CP overestimates performance and time to exhaustion. Housh et al. found that CP overestimated time to exhaustion based on 4 trials and power outputs ranging from 172 - 360 watts. Mean time to fatigue at CP was 33 minutes, not significantly different from the preset predicted time to fatigue of 60 minutes. Statistically there was no significant difference, but the error was large (27 minute difference in actual versus predicted time) when applied to a performance environment (Housh et al.). In an attempt to correct for some of these gross inaccuracies of CP predicting time to fatigue, Morton (1994) suggested ramp protocols for determination of CP would allow for a more accurate prediction when forming CP parameter estimates. Morton showed that mean CP was 161 watts, significantly lower than previous CP estimates (Housh et al.). In theory Morton's analysis would provide a more conservative CP estimate, and consequently a greater time to exhaustion although Morton does not actually perform a time to fatigue test at CP. Kolbe, Dennis, Selley, Noakes, & Lambert (1995) reported on the inaccuracies of CP in predicting running times over a variety distances. It was concluded that CP estimates are most highly correlated with 10 kilometer race times ($r = 0.85$, $p > 0.0001$) but are overall poor predictors of running times in male distance runners. The ability to accurately form CP estimates has been based largely on the number of trials used to form the CP estimate. Two studies, one involving kayakers (Clingeleffer, McNaughton, & Davoren, 1994a) the other utilizing cycle ergometry (Housh, Housh, & Bauge, 1990) both concluded that two trials or power loadings are sufficient to accurately form CP estimates. Each study found no statistical difference with CP values derived from two trials versus CP determined from more than two trials. Morton, Green, Bishop, & Jenkins (1997) recently have concluded that ramp protocol estimates do not differ significantly from constant power trials for determination of CP. The ramp protocol was favoured by Morton et al. for two reasons: subjects preferred the ramp protocol and secondly there was better motivation to provide a maximal effort in each trial.

Anaerobic Threshold And Critical Power:

An initial investigation involving the relationship of CP and blood lactate found that maintenance of CP in cycle ergometry over 60 minutes was only achieved in 2 out of 8 highly trained cyclists (Jenkins & Quigley, 1990). Steady state blood lactates were reported at 8.9 mmol in the last 20 minutes of the CP test and it was concluded that CP was an effective way to assess exercise intensity (Jenkins & Quigley). Comparisons of CP lactate levels to concentrations of lactate at Onset of Blood Lactate Accumulation (OBLA) (Housh et al., 1991) or Maximal Lactate Steady State (MLSS) (McLellan & Cheung, 1992) both found CP lactate levels greater than MLSS (Individual Anaerobic Threshold, [IAT]) or OBLA in cycle ergometry. McLellan & Cheung found a significant difference in PO occurring at IAT (235 Watts) versus CP (265 Watts); Housh et al. found CP to occur at 230 Watts which was greater than the 180 Watts which elicited OBLA. Clingeleffer, McNaughton, & Davoren (1994b) stated that CP was significantly higher than OBLA (4 mmol of blood lactate) in trained male kayakers. Clingeleffer et al. concluded that CP and Anaerobic Threshold were significantly different physiological points in kayaking. In a related study Stegman & Kinderman (1982) found that trained rowers maintained an intensity equal to their individual anaerobic threshold (steady state 4 mmol) for 50 minutes. A recent study with trained cyclists (Petersen, Dressendorfer, & Stickland, 1996) defined Critical Aerobic Power (CAP) as the maximal sustainable power output over a 20 km simulated cycling time trial. CAP occurred at a power output equal to 85 % $\dot{V}O_2$ max and a mean blood lactate of 7.2 mmol for the 20 km trial. Jenkins & Quigley found a similar mean blood lactate of 8.9 mmol in the last 20 minutes of exercise at CP over a 30 minute cycling trial.

Critical Power And Training:

A number of studies have investigated the influence of training on CP values and associated respiratory or metabolic indices. Gaesser & Wilson (1988) investigated the effects of interval and continuous training on CP determined during cycle ergometry in 14 males of average fitness. Both interval and continuous groups showed an increase in CP values with the interval group improving 33 watts versus the continuous group (27 watts). Training consisted of 3 times a week for 6 weeks with the interval group performing 10 x 2 minute intervals at a power output equal to $\dot{V}O_2$ max per training session. The continuous group cycled at 50 % $\dot{V}O_2$ max for 40 minutes per session 3 times a week for 6 weeks. Loads were not corrected over the six week period and attendance was 100 % for each group. CP was equal to 75 % of peak and was shown to have stable $\dot{V}e$, blood lactate and $\dot{V}O_2$ measurements (Gaesser & Wilson). Jenkins & Quigley (1992) found an improvement in CP values after 8 weeks of cycle ergometry training. The effects of moderate intensity endurance training showed a significant positive increase of 59 Watts from initial CP values, whereas the control group had no significant improvement. The trained group was able to maintain a power output of 242 watts (pretraining = 190 watts) over 40 minutes of cycling, the controls were limited to a 16 watt increase in their 40 minute cycling trial (194 watts,[pre]; 210 watts,[post]).The increase in controls power outputs was attributed to a learning effect gained from the initial cycling trials (Jenkins & Quigley). The effect of 6 weeks of resistance training on time to exhaustion at CP and AWC in cycle ergometry was reported by Bishop & Jenkins (1996). Anaerobic work capacity was sensitive to resistance training (Pre- 21.5kJ, Post- 29.0kJ, $p<0.05$) but endurance ability (time to exhaustion at CP; Pre-1570s, Post-1717s, $p<0.05$) was not influenced by weight training in the 16 male subjects (Bishop & Jenkins).

A recent study involving speed skaters (Smith, Lefort, & Kranenburg, 1994) showed no significant increase in CP after a 10 day taper program (volume decreased by 20% from the previous 6 week training load). Significant increases were observed in Anaerobic Work Capacity (AWC) (23%, $p<0.05$) and maximal lactate concentrations (10%, $p< 0.06$) at CP over the 10 day taper. Possible explanations of why CP did not significantly change include; testing occurred on a cycle ergometer (sport specificity) and inadequate reduction in training volume to see any positive increases in CP values. Poole, Ward, & Whipp (1990) compared changes in different physiological parameters and CP values after 7 weeks of intense cycle ergometry training and did show similar results to previous research (Gaesser & Wilson). Ten x 2 minute intervals were undertaken each session, 3 times per week for seven weeks at an intensity equal to 105 % of their initial tolerable limit for 2 minutes of exercise. Increases in lactate threshold (24%) peak, $\dot{V}O_2$ (15%) and CP (15%) were seen although AWC was not significantly different post training. CP represented the upper power limit at which $\dot{V}O_2$ and blood lactate remained stable and intensities above CP would result in imminent fatigue due to a falling blood pH and a variable $\dot{V}O_2$ (Poole et al.).

Critical Velocity:

A recent adaptation of the power-duration relationship, replaces power with distance in the various CP equations to predict time over a given distance. The relationship between distance and time has many similar qualities to the power-time relationship and has been coined Critical Velocity (CV). The distance-time relationship can be used for swimming, running, triathlons, cross country skiing and rowing.

Critical Velocity And Swimming:

A number of factors in a sport environment need to be controlled before CV theories can be applied. The sport of swimming is aptly suited to Critical Velocity for a number of reasons: controlled environment, duration of swimming events, and ease of measurement for the parameters distance and time in CV trials. Initially, Wakayoshi, Ikuta, et al. (1992) sought to determine CV's validity as an index of swimming performance. Subjects swam in a swim flume at six different water velocities ranging from 1.2 to 1.7 $m \cdot s^{-1}$. Time to fatigue was then recorded at each velocity, distance was calculated, and CV values were created based on the slope of relationship between distance and time over the 6 different speeds. CV correlates for velocity at Onset of Blood Lactate Accumulation (vOBLA), and $\dot{V}O_2$max were $r = 0.9$ ($p<0.01$) and $r = 0.1$ (ns), respectively. Due to the significant correlation between vOBLA (4 mmol blood lactate) and CV, it was concluded that CV was a good index for monitoring swimming performance. As well, CV has few of the negative methodological or economic factors associated with lactate threshold or ventilatory threshold testing (Wakayoshi, Ikuta, et al., 1992). Following the initial study, CV was applied in a pool setting by Wakayoshi, Yoshida, Udo, et al. (1992). A comparison was done between CV parameters formed by swimming at maximal intensity over 4 different distances in the pool versus 4 different velocities in the swim flume. There was no significant difference between the CV in the pool and CV in the flume (1.555 $m \cdot s^{-1}$; 1.543 $m \cdot s^{-1}$ respectively) but both CV values were greater than the vOBLA calculated at 1.494 $m \cdot s^{-1}$. With no significant difference between the two CV values Wakayoshi, Yoshida, Udo, et al. (1992) concluded that CV may be a valuable tool for assessing endurance performance in the pool using time measures created from actual distances swum. Wakayoshi, Yoshida, Kasai, et al. (1992) found with trial lengths of 50, 100, 200, and 400 metres to create the CV estimate (with 17 male swimmers), that a correlation between CV and velocity over 400 metres was significant ($r = 0.99$, $p<0.01$). This high correlation was due to the fact that 400 metres was used both to create the CV estimate and as the comparison velocity calculated from the 400 metre distance. As well the results indicated that CV was a good index of swimming performance and a marker of fatigue threshold (Wakayoshi, Yoshida, Kasai, et al., 1992). A follow up study (Wakayoshi et al., 1993) validated CV as an indice of Maximal Lactate Steady State (MLSS) using only two trials (200m and 400m) to form the CV line of best fit. Following CV determination trials each subject was required to swim three 1600 metre trials one each at 98%, 100% and 102% of their predetermined CV. Blood lactate was taken every 400 metres to determine steady state of the lactate profile. At 100% CV, a steady state of approximately 3.2 mmol was found whereas at 102% CV a progressive rise in blood lactate was shown. It was concluded that CV was a significant physiological marker of MLSS in male swimmers based on 2 point determination of CV. Data collected for the National Swimming Program (Smith, 1992) supported the research of Wakayoshi, Yoshida, Udo, et al. (1992). Smith, found that swimming trials of 1200, 600, 200 and 50 metres created a CV parameter estimate similar to the velocity over the 1200 metre trial (CV = 1.306 $m \cdot s^{-1}$ versus actual 1.333 $m \cdot s^{-1}$). Hill, Steward, & Lane (1995) applied CP concepts with young swimmers (age range 8-18 years, N = 86) using three different CV models and a variety of different trial lengths (determined by the age of the swimmer). The linear distance-time model gave the highest correlation between the velocity of the longest trial (V long) swum (not used to form the CV estimate) and the CV parameter estimates.

Critical Velocity And Running:

Validation of CV in running was done by Hughson, Orok, & Staudt (1984) using a linear power 1/time model adapted to replace power output with velocity on the y axis. Correlation coefficients of $r = 0.979$ to 0.997, $p < 0.05$ were found based on trials run at 6 different velocities ranging from 19.2 to 22.4 $km \cdot hr^{-1}$ set to fatigue the subject between 2 - 12 minutes. It was concluded that CP modelling was a valid estimate of running performance (Hughson et al.). Pepper, Housh, & Johnson (1992) used a non-linear velocity-time model to predict time to exhaustion at CV. Theoretically, CV has been defined as the maximal sustainable velocity which can be held for a very long time which Pepper et al. believed corresponded to 60 minutes. By having subjects run to fatigue at velocities ranging from 12.88 to 21.74 $km \cdot hr^{-1}$ CV estimates were created. Subjects then completed trials to fatigue at 70%, 85%, 100% 115% and 130% CV. At 100% CV time to fatigue occurred in 16.4 minutes, a 43.6 minute difference from the predicted time to fatigue of 60 minutes. At 85% of CV, time to fatigue was 55 minutes which would indicate that based on the velocities used to form CV, performance and time to fatigue were overestimated (Pepper et al.). Using the same model as Pepper et al., McDermott, Forbes, & Hill (1993) applied treadmill running and CV estimates (Hughson et al.; Pepper et al.) to outdoor running using trials of 400, 800, 1600, 5000 and 10,000 metres. The 3 shortest trials were used to form CV estimates and showed no statistical difference between actual versus predicted time over 10,000 metres (41.04 min {predicted}; 43.29 min {actual}). Ability of CV to accurately predict times over 10,000 metres (McDermott et al.) running outside were supported by Kranenburg & Smith (1994). Kranenburg & Smith tested nine highly trained males asked to perform trials of 907, 2267.5, and 4081.5 metres forming CV estimates based on those trial lengths. CV was estimated at 291 m·min^{-1} and had no significant difference when compared to race speed over 9.8 km (293 m·min^{-1}). Over a marathon distance Florence & Weir (1997) found that CV (estimated from 4 treadmill tests and a linear distance - time model) was significantly correlated to marathon finishing time (R^2=0.76, $p<0.05$). The significance of marathon finish time and CV was overshadowed by the gross difference in actual marathon speed for the 12 subjects (3.07 m·s^{-1}) versus predicted speed (CV = 4.43 m·s^{-1}) (Florence & Weir). Kachouri et al. (1996) most recently examined the difference in CV parameters when estimated from continuous trials versus intermittent work within each trial. The continuous protocol consisted of running to fatigue at 95% and 105% of the velocity elicited from an initial running test called the Montreal Track Test (vMTT) (total time and distance recorded). The interval protocol consisted of running to half of the total distance of the continuous trials at each intensity (95 and 105% vMTT) with a rest equal to the time taken to run half the continuous distance. The subject then resumed the intensity and repeated the protocol until exhaustion. Total accumulated distance was greater in the interval protocol but CV for interval versus continuous protocol (4.6 m·s^{-1} {continuous}; 4.56 m·s^{-1} {interval}) was not significantly different. It was concluded that the method employed to create the CV parameter does not effect the parameter value.

Treadmill testing and track running are both used in CV research to create parameter estimates. Norris & Smith (1996) examined the difference in biological load from treadmill to track running in 12 university age recreational male runners. Blood lactate measurement was used as the marker to determine equivalency of load in the two running modalities. Track testing occurred at 3 different intensities corresponding to 88, 94 and 100% CV for 6 minutes each trial. Blood lactate was taken immediately post exercise to determine concentration at that intensity. Treadmill testing occurred at 3 different grades (0, 1, and 2%) for each intensity (88, 94, and 100% CV) with a duration of 6 minutes per trial. It was concluded that at 1% grade on the treadmill the equivalent energy expenditure would occur on the track at any of the given intensities. The reliability of treadmill testing was questioned by Hill et al. (1996). In a single treadmill test at 300 m·min^{-1} to fatigue various physiological parameters were analysed. In a retest at the initial test speed $\dot{V}O_2$ kinetics (time constant of the response) were unchanged but differences in $\dot{V}O_2$max (50 {test 1} versus 48 ml·kg^{-1}·min^{-1} {test 2}), and time to exhaustion (140 seconds {test 1} versus 117 seconds {test 2}) were significantly different.

Critical Velocity In Other Sports:

Other performance settings where CV theory has been utilized include speed skating and rowing. Smith & Norris (1996) had nine male and six female speed skaters participate in a study where 5000 metre (3000 m for females) and 1500 metre times had significant correlations to MLSS, VO_2 max and Maximum Work Done in 2 Minutes (MW2M). Critical Power testing was utilized to determine the appropriate loads needed for each subject in the MW2M using cycle ergometry. Testing for both the VO_2 max and Maximum Work Done in 2 Minutes were done on a cycle ergometer whereas the MLSS testing was done while skating on ice. Fifteen hundred metre times had significant correlations to MW2M ($r = .98$ {males} and $r = 0.9$ {females}, $p<0.05$) and 5000 metre times for males and 3000 metres for females had significant correlations with MLSS ($r = 0.096$ {males} and $r = 0.99$ {females}, $p<0.05$). A rowing study by Kennedy & Bell (1996) found that the predictive ability of CV parameters for 2000 metres in simulated rowing was excellent. Predicted time over 2000 metres was 400 seconds versus actual time of 410 seconds for 18 male rowers. Zaryski, Smith, & Wiley (1994) compared event speed to CV parameter estimates in Olympic distance triathlons. The ability to predict times for each leg of the triathlon was good for swimming (event speed = 101.8% of CV) and the cycling portion of the triathlon was performed at 97.8% of predicted CV for the 9 male triathletes. Running was approximately 5% off the predicted velocity for the run, and error was attributed to the length of the trials used to form each parameter estimate.

Anaerobic Work Capacity:

CV or CP research has primarily focused on the aerobic nature of parameter estimates (i.e. significant correlations to IAT, MLSS, OBLA, $\dot{V}O_2$max) or the ability to predict endurance performance. CP models create not only an aerobic measure but also a y-intercept value (linear distance- time model) that seems to correlate with Anaerobic Work Capacity (AWC) or the amount of work done without oxygen (CP models). Anaerobic Work Capacity is best defined as the distance travelled or work performed using the energetic reserve of muscle without any predominate contribution of oxygen to supplement the rephosphorylation of ATP.

The purpose of many investigations in the CP (CV) area stems from the question "does anaerobic metabolism play a role in endurance performance"? Initial investigations include Bulbulian, Wilcox, & Darabos (1986) who calculated the amount of anaerobic work in Joules based on 3 trials to fatigue on the cycle ergometer. A linear work time model was used to calculate AWC (y-intercept) in Joules, values ranging from 8000 to 28 400 Joules. Subjects ran an 8.05 km running trial at maximum intensity and AWC contributed significantly (58% total shared variance) to predicting race performance in the 8.05 km run. Conflicting results (Housh, Johnson, Mcdowell, Housh, & Pepper, 1992) found that anaerobic running capacity (y-intercept) had little correlation to peak plasma lactate ($r = 0.06$, ns). Based on 4 treadmill trials to fatigue (formation of CV parameter estimates), a linear distance-time model and a maximal running trial to illicit peak blood lactate (time to fatigue = 65 seconds at 9% grade) the ability to predict or infer anaerobic running capacity was weak (Housh et al.). Validation of AWC as a marker of anaerobic ability was done by Jenkins & Quigley (1991) in cycle ergometry. CP values were elicited from 3 maximal trials of 300, 350 and 400 watts; anaerobic capacity values were measured from 5 one minute maximal exertion trials each separated by 5 minutes rest where total anaerobic work was calculated by the cumulative values of each of the 1 minute work bouts. Correlation of the y-intercept value garnered from the CP model versus the value from the anaerobic work test were significant ($r = 0.074$, $p<0.05$). Blood pH at the end of anaerobic work test was also significantly related to AWC ($r = 0.92$, $p<0.05$). It was concluded that the capacity for high intensity interval work was well represented by the y-intercept or AWC. Hill & Smith (1993) believed that oxygen deficit was the most acceptable measure of anaerobic capacity and used cycle ergometry with CP modelling to validate AWC. Mean values for the 26 subjects had a significant correlation of $r = 0.77$, $p<0.01$ between the two estimates of anaerobic capacity; AWC based on CP testing and oxygen deficit garnered from the CP trials. Building on the theory that AWC may be highly correlated to oxygen deficit Hill, Rose, & Smith (1993) and Hill & Smith (1994) both found that use of different models to predict AWC gave large variations in the values formed. Linear power-time, linear work-time and nonlinear power-time models all gave mean values for the 26 subjects which were different. The Standard Error of Estimate (SEE) was high (> 20%) between values gained from the 3 models, showing that the type of model used to form the AWC value was important. Effects of training on estimates of AWC (Jenkins & Quigley, 1993) was done with 8 male subjects (trained group) and 7 controls in cycle ergometry. The purpose was to examine the effects of 8 weeks of repeated high intensity interval exercise (60 second work bouts at maximum intensity were done 5 times per session with 3 sessions per week) on the initial estimate of AWC (linear work-time model). The trained group had significantly different AWC and CP values post training (AWC, +6.6 kJ; CP, +18 Watts). It was determined that AWC estimates are sensitive to intense interval exercise and evaluation of anaerobic capacity can be interpreted from CP testing. It must be noted that although there are relatively few published reports in the area of AWC validation, there are a number of CP studies that have looked at AWC as an aside to the primary purpose of the study (validation of CP).

Critical Power Models:

Monod & Scherrer (1965) used a linear work-time model to form parameters for CP and AWC. This model has been the standard on which other models were based and has been used as the most appropriate model for a number of research investigations (Housh et al., 1991; Jenkins & Quigley, 1992; Kolbe, Dennis, Selley, Noakes, & Lambert, 1995; Overend, Cunningham, Paterson, & Smith, 1992). Modification of the linear work-time model to a linear work-1 / time model changed the value of CP from a slope to a y-intercept estimate. The conversion of time to a fractional value allowed the larger time values to be closer to the axis of origin. Longer trials become more influential with this model (more conservative estimate of CP). The third popular model has a hyperbolic relationship between power output and time and was deemed the nonlinear power-time model. The power asymptote (CP) is the upper limit of sustainable power over a very long time. Many researchers have used this model and rationalized its usefulness (McLellan & Cheung, 1992; Moritani, Nagata, deVries, & Muro, 1981; Poole, Ward, & Whipp, 1990; Talbert, Smith, Scarborough, & Hill, 1991). Other models recently introduced include a modification of the hyperbolic model (Peronnet & Thibault, 1989), an exponential model (Hopkins, Edmond, Hamilton, Macfarlane, & Ross, 1989) and a 3 parameter non-linear model (Gaesser, Carnevale, Garfinkel, Walter, & Womack, 1995). Validation of the exponential model (Hopkins et al.) in short running events had the following conclusions. As a model the fit of all data was strong, although caution was stressed in accuracy of the model if the length of the shortest CP trial was less than 10 seconds. Hopkins et al. found correlations between 30 second Wingate test (cycle ergometry) and AWC values were significant ($r = 0.73$-0.81, $p<0.05$) concluding that the exponential model may be a useful tool for inferring anaerobic ability. Gaesser, Carnevale, Garfinkel, & Walter (1990) stated that the two linear models and the nonlinear model, gave different CP values. The nonlinear model gave the most conservative and accurate estimation of CP with the linear models both overestimating performance(Gaesser, Carnevale, Garfinkel, & Walter, et al.). Smith & Hill (1992) felt that the small sample size ($n = 5$) of the Gaesser, Carnevale, Garfinkel, and Walter, et al. investigation was the determining factor in the different CP values. Therefore using 47 subjects Smith & Hill showed no difference in CP values (189.5 Watts {Nonlin pt}, 190 Watts {Lin p 1/t}, 189.7 Watts {Lin pt t}) formed from the same 3 models as the Gaesser et al. study.

Gaesser, Carnevale, Garfinkel, Walter, & Womack (1995) compared 5 different models in the estimation of CP and found a three parameter model (addition of a parameter called Maximal Instantaneous Power {Pmax}) gave the most accurate values for CP (CP correlated to VT in all models). Effect of pedal cadence on CP estimation was done by Carnevale & Gaesser (1991) and Hill, Smith, Leuschel, Chasteen, & Miller (1995). Carnevale & Gaesser initially reported that based on CP done at 60 versus 100 rpm (nonlinear power-time model) the 60 rpm trials gave CP estimates 21 watts greater than the 100 rpm trials.

It was concluded that the 60 rpm gave a better estimation of aerobic ability and a more accurate value for CP. Hill et al. (1995) used a similar protocol to the Carnevale & Gaesser (1991) investigation but added a variable rpm protocol as well. The results indicated that a variable cadence (individual choice of cadence within each test) when performing the CP trials gave the most accurate and reliable CP values when formed with three different CP models. At variable cadence CP was no more than 2 watts different between the 3 models used. Morton & Hodgson (1996) in a recent review article add the following points concerning modelling : the hyperbola has the best fit of data for trial lengths of 2 - 15 minutes but the modification of the basic formula increases accuracy of CV and allows data fitting to range from 5 seconds to 2 hours.

Related Topics And Research:

Critical power and critical velocity research are based on a variety of different fundamentals including pacing strategy and prediction of performance. The ability to create pacing strategies in a performance setting is important for many reasons. Foster, Schrager, Snyder, & Thompson (1994) reviewed the importance of pacing as it relates to performance. Recommendations on pacing over the duration of an event include creating models that start to account for fatigue as duration increases. In CP or CV research the ability to best predict performance or create pacing strategies may lie with the exponential model which includes a time constant and does not have a completely linear relationship. An associated test of aerobic ability was done by Boulay, Hamel, Simoneau, & Lortie (1984). A simple protocol of one cycle ergometer test 90 minutes in length in which total work was calculated was done with thirty subjects. Reliability of the test was high ($r = 0.99$, $p<0.01$) and has good predictive ability of aerobic capacity (ie. the higher the total work in 90 minutes the greater the aerobic ability).

The predictive ability of CP and CV is useful but other parameters such as $\dot{V}O_2$ at threshold and velocity at threshold have also been used to predict or monitor performance. Recommendations by Billat (1996) for interpreting blood lactate values as a measure for training rowers include training at or above threshold will have a positive effect on physical fitness. Prediction of marathon times based on velocity at which anaerobic threshold were elicited (Rhodes & McKenzie, 1984) found that predicted time for a group of 18 male runners for the marathon was only 103 seconds different from actual time (2:53:49 {predicted}, 2:52:06 {actual}). CV and CP have been correlated to velocities at which threshold occur (IAT, OBLA, MLSS) but rarely to $\dot{V}O_2$max. Significance of Velocity at $\dot{V}O_2$max (vVmax) as an indicator of aerobic power and running performance was shown in a recent review (Billat & Koralsztein, 1996). An interesting relationship exists at $\dot{V}O_2$max: the higher one's $\dot{V}O_2$max the smaller the tlim at the velocity which elicits that $\dot{V}O_2$max. This relationship may be due to the positive relationship between $\dot{V}O_2$max values and the velocity at which $\dot{V}O_2$max would occur. The velocity at which someone with a large $\dot{V}O_2$max could run would be greater than someone with a smaller value, imparting that the faster velocity would incur greater anaerobisis and not tolerate the velocity as well as the lower $\dot{V}O_2$max value. Hill & Rowell (1996a) found that based on 5 definitions of vVmax each determined by a distinct method, the values were significantly different. Values ranged from 247 $m \cdot min^{-1}$ to 267 $m \cdot min^{-1}$ signifying the uniqueness of each protocol in defining the velocity at which $\dot{V}O_2$max occurs. Hill & Rowell (1996b) in a related article found that time to exhaustion (tlim) at vVmax was not a good indicator of anaerobic capacity in subjects. Anaerobic Threshold (44 %) and oxygen deficit (26%) in combination accounted for only 70% of variability associated with tlim at vVmax (Hill & Rowell, 1996b). Hill's interest in anaerobic capacity, oxygen deficit has created a better understanding of the processes at work during high intensity short duration exercise. Hill (1996) has found that calculation of oxygen deficit through 4 maximal intensity cycle ergometry trials creates values not significantly different from the conventional sub-maximal methods used to obtain oxygen deficit data.

Summary:

The area of "CRITICAL" testing has many applications in the sport performance setting. Parameter estimates can be useful in monitoring changes in performance, inferring physiological parameters without expensive equipment, and prediction of performance times. Most research in the area involves Critical Power testing, Critical Velocity testing, and/or formation of Anaerobic Work Capacity values.

Critical Power testing was originally performed on synergistic muscle groups (Monod & Scherrer, 1965) and applied to cycle ergometry work (Moritani, Nagata, deVries, & Muro, 1981). Critical Power research has been limited to specific modalities (primarily cycling) and has traditionally used very short high intensity trials to create Critical Power estimates (Morton, 1994). Protocols using very short trials to create Critical Power estimates often over predict performance (Housh, Housh, & Bauge, 1989) and create fatigue at Critical Power more quickly than estimated ones (Jenkins & Quigley, 1990). By definition, Critical Power is the upper limit of sustainable power output only leading to fatigue after a very long time (Monod & Scherrer, 1965) contrary to the findings in the following studies (Housh et al., 1989; Jenkins & Quigley, 1990; McLellan & Cheung, 1992; Morton, 1994). Methodological considerations as to why Critical Power overestimates performance include using trials that are too short to create a conservative estimate of power output over a prolonged period of time and use of appropriate models to form the parameter. Most Critical Power methodology involves a minimum of 2 trials (maximum 5 trials) at maximal intensity with a predetermined protocol to end the trial (eg. to exhaustion or until a predetermined drop in power output or pedal cadence was seen). Motivation of the subject to perform numerous trials at maximal intensity may play a role in determination of values, and use of highly trained athletes (Jenkins & Quigley, 1990) versus Moritani et al. (1981) using average fitness college students provides different values for Critical Power. Critical Power testing can be practical when very short trials are used to form the CP value. Consequently short CP trials lead to a greater error in predicting long performances, therefore caution must be used when selecting trial lengths for the purpose of predicting performance.

Validation of Critical Power and Critical Velocity as a marker of aerobic ability has been found by a number of researchers (Housh et al., 1991; Poole, Ward, & Whipp, 1990; Talbert, Smith, Scarborough, & Hill, 1991) but may overestimate specific aerobic parameters such as IAT (McLellan & Cheung, 1992), Anaerobic Threshold (Clingeleffer, McNaughton, & Davoren, 1994b), and OBLA (Wakayoshi et al., 1993). Generally Critical Power and Critical Velocity estimates correlate significantly with indices of aerobic fitness, but often the CV value has overestimated the aerobic marker.

Critical Velocity research has been used in a variety of sports including swimming, running, triathlons, and a preliminary study of rowing. Prediction of performance in Critical Velocity research has found significant correlations between parameter estimates and velocity over 400 metres in swimming, $r = 0.864$, $p<0.01$ (Wakayoshi, Ikuta, et al., 1992), predicted and actual rowing times over 2000 metres, $r = 0.95$, $p<0.05$ (Kennedy & Bell, 1996), predicted and actual running times over 10,000 metres, $r = 0.97$, $p<0.001$ (McDermott, Forbes, & Hill, 1993), critical versus event speed over 9.8 kilometres running, $r = 0.93$, $p<0.001$ (Kranenburg & Smith, 1994) and predicted versus actual event speed in an Olympic distance triathlon, $r = 0.82$, $p<0.05$ (Zaryski, Smith, & Wiley, 1994). Being able to predict performance in timed events such as swimming, running, rowing and triathlons would be important for aiding sport performance.

Due to the two parameter nature of Critical Power models a second value, Anaerobic Work Capacity has been created. It has been shown to be an accurate assessment of anaerobic ability (Hill & Smith, 1993) and was used as a marker of performance in short duration events (Hopkins, Edmond, Hamilton, Macfarlane, & Ross. 1989). Validity of Anaerobic Work Capacity has been questioned and is currently being investigated as an accurate marker of anaerobic work. The effect that the CV or CP model has on determining the CV or AWC value seems to be important and much research has revolved around this question (Gaesser, Carnevale, Garfinkel, & Walter, 1990; Hill, Rose, & Smith, 1993; Smith & Hill, 1992). Primarily, 3 models have been used to create parameter estimates (linear work-time, linear power-1/time, and nonlinear power-time) but the addition of a 3 parameter nonlinear model and an exponential model have contributed new directions to the area. Further research involving the validation of such models is needed and the use of multiple models in providing CV parameter estimates should be investigated. Other related fields share commonalities with Critical Power and Critical Velocity testing. The study of ventilatory parameters, $\dot{V}O_2$max and blood parameters to assess, predict and monitor performance are large and distinct areas of research. Borrowing concepts and ideas from other areas will continue to further CP and CV research and contribute to the body of knowledge in the area of sport performance.

REFERENCES

Billat, L. V. (1996). Use of blood lactate measurements for prediction of exercise performance and for control of training. Sports Medicine, 22 (3), 157-175.

Billat, L. V., & Koralsztein, J. P. (1996). Significance of the velocity at $\dot{V}O_2$ max and time to exhaustion at this velocity. Sports Medicine, 22 (2), 90-108.

Bishop, D., & Jenkins, D. G. (1996). The influence of resistance training on the critical power function and time to fatigue at critical power. The Australian Journal of Science and Medicine in Sport, 28 (4), 101-105.

Boulay, M. R., Hamel, P., Simoneau, J. A., & Lortie G. (1984). A test of aerobic capacity: Description and reliability. Canadian Journal of Applied Sport Sciences, 9 (3), 122-126.

Bulbulian, R., Wilcox, A. R., & Darabos, B. L. (1986). Anaerobic contribution to distance running performance of trained cross-country athletes. Medicine and Science in Sports and Exercise, 18 (1), 107-113.

Carnevale, T. J., & Gaesser, G. A. (1991). Effects of pedalling speed on the power-duration relationship for high-intensity exercise. Medicine and Science in Sports and Exercise, 23 (2), 242-246.

Clingeleffer, A., McNaughton, L. R., & Davoren, B. (1994a). Critical power may be determined from two tests in elite kayakers. European Journal of Applied Physiology and Occupational Physiology, 68, 36-40.

Clingeleffer, A., McNaughton, L. R., & Davoren, B. (1994b). The use of critical power as a determinant for establishing the onset of blood lactate accumulation. European Journal of Applied Physiology and Occupational Physiology, 68, 182-187.

DeVries, H. A., Moritani, T., Nagata, A., & Magnussen, K. (1982). The relation between critical power and neuromuscular fatigue as estimated from electromyographic data. Ergonomics, 25 (9), 783-791.

DeVries, H. A., Tichy, M. W., Housh, T. J., Smyth, K. D., Tichy, A.M., & Housh, D. J. (1987). A method for estimating physical work capacity at the fatigue threshold. Ergonomics, 30 (8), 1195-1204.

Florence, S., & Weir, J. P. (1997). Relationship of critical velocity to marathon running performance. European Journal of Applied Physiology and Occupational Physiology, 75, 274 - 278.

Foster, C., Schrager, M., Snyder, A. C., & Thompson, N. N. (1994). Pacing strategy and athletic performance. Sports Medicine, 17 (2), 77-85.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., & Walter, D. O. (1990). Modelling of the power-endurance relationship for high intensity exercise (Abstract). Medicine and Science in Sport and Exercise, 22 (2), 95.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., Walter, D. O., & Womack, C. J. (1995). Estimation of critical power with nonlinear and linear models. Medicine and Science in Sport and Exercise, 27 (10), 1430-1438.

Gaesser, G. A., & Wilson, L. A. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high- intensity exercise. International Journal of Sports Medicine, 9 (6), 417-421.

Hill, D. W. (1996). Determination of accumulated O_2 deficit in exhaustive short-duration exercise. Canadian Journal of Applied Physiology, 21(1), 63 - 74.

Hill, D. W. (1993). The critical power concept a review. Sports Medicine, 16 (4), 237-254.

Hill, D. W., & Rowell, A. L. (1996a). Running velocity at $\dot{V}O_2$ max. Medicine and Science in Sports and Exercise, 28 (1), 114-119.

Hill, D. W., & Rowell, A. L. (1996b). Significance of time to exhaustion during exercise at the velocity associated with $\dot{V}O_2$ max. European Journal of Applied Physiology and Occupational Physiology, 72, 383 - 386.

Hill, D.W., Rose, L. E., & Smith, J. C. (1993). Estimates of anaerobic capacity derived using different models of the power-time relationship (Abstract). Medicine and Science in Sports and Exercise, 25 (5), 606.

Hill, D. W., & Smith, J. C. (1993). A comparison of methods of estimating anaerobic work capacity. Ergonomics, 36 (12), 1495-1500.

Hill, D. W., & Smith, J. C. (1994). A method to ensure the accuracy of estimates of anaerobic capacity derived using the critical power concept. The Journal of Sports Medicine and Physical Fitness, 34 (1), 23-37.

Hill, D. W., Smith, J. C., Leuschel, J. L., Chasteen, S. D., & Miller, S. A. (1995). Effect of pedal cadence on parameters of the hyperbolic power -time relationship. International Journal of Sports Medicine, 16 (2), 82-87.

Hill, D. W., Steward, R. P., & Lane, C. J. (1995). Application of the critical power concept to young swimmers. Pediatric Exercise Science, 7, 281-293.

Hill, D. W., Williams, C. S., Smith, M. S., Kinser, K. B., Trevino, T. L., Rowell, A. M., & Mealing, D. L. (1996). Reproducibility of responses to exhaustive constant velocity running tests (Abstract). The Physiologist, 39 (5), 40.4.

Hopkins, W. G., Edmond, I. M., Hamilton, B. H., Macfarlane, D. J., & Ross, B. H. (1989). Relation between power and endurance for treadmill running of short duration. Ergonomics, 32 (12), 1565-1571.

Housh, T. J., DeVries, H. A., Housh, D. J., Tichy, M. W., Smyth, K. D., & Tichy, A. M. (1991). The relationship between critical power and the onset of blood lactate accumulation. The Journal of Sports Medicine and Physical Fitness, 31, 31-36.

Housh, D. J., Housh, T. J., & Bauge, S. M. (1989). The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. Ergonomics, 32 (8), 997-1004.

Housh, D. J., Housh, T. J., & Bauge, S. M. (1990). A methodological consideration for the determination of critical power and anaerobic work capacity. Research Quarterly for Exercise and Sport, 61 (4), 406- 409.

Housh, T. J., Johnson, G. O., McDowell, S. L., Housh, D. J., & Pepper, M. L. (1992). The relationship between anaerobic running capacity and peak plasma lactate. The Journal of Sports Medicine and Physical Fitness, 32, 117-122.

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A high velocity treadmill running test to assess endurance running potential. International Journal of Sports Medicine, 5, 23-25.

Jenkins, D. G., & Quigley, B. M. (1990). Blood lactate in trained cyclists during cycle ergometry at critical power. European Journal of Applied Physiology and Occupational Physiology, 61, 278- 283.

Jenkins, D. G., & Quigley, B. M. (1991). The y-intercept of the critical power function as a measure of anaerobic work capacity. Ergonomics, 34 (1), 13-22.

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

Jenkins, D. G., & Quigley, B. M. (1993). The influence of high intensity exercise training on the Wlim-Tlim relationship. Medicine and Science in Sports and Exercise, 25 (2), 275-282.

Kachouri, M., Vandewalle, H., Billat, V., Huet, M., Thomaidis, M., Jousselin, E., & Monod, H. (1996). Critical velocity of continuous and intermittent running exercise: An example of the limits of the critical power concept. European Journal of Applied Physiology, 73, 484-487.

Kennedy, M., & Bell, G. (1996). Prediction of 2000 metre rowing times using critical velocity parameter estimates (Abstract). The Physiologist, 39 (5), 40.8.

Kolbe, T., Dennis, S. C., Selley, E., Noakes, T. D., & Lambert, M. I. (1995). The relationship between critical power and running performance. Journal of Sport Sciences, 13, 265-269.

Kranenburg, K., & Smith, D. J. (1994). Prediction of 9.8 km performance in elite runners using critical speed (Abstract). Canadian Journal of Applied Physiology, 19, 24P.

McDermott, K. S., Forbes, M. R., & Hill, D.W. (1993). Application of the critical power concept to outdoor running (Abstract). Medicine and Science in Sports and Exercise, 25 (5), 610.

McLellan, T. M., & Cheung, K. Y. (1992). A comparative evaluation of the individual anaerobic threshold and the critical power. Medicine and Science in Sports and Exercise, 24 (5), 543-550.

Monod, H., & Scherrer, J. (1965). The work capacity of synergic muscle groups. Ergonomics, 8, 329-338.

Moritani, T. A., Nagata, H. A., deVries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24, 339-350.

Morton, R. H. (1994). Critical power test for ramp exercise. European Journal of Applied Physiology and Occupational Physiology, 69, 435-438.

Morton, R. H., Green, S., Bishop, D., & Jenkins, D. G. (1997). Ramp and constant power trials produce equivalent critical power estimates. Medicine in Science and Sports and Exercise, 29 (6), 833 - 836.

Morton, R. H., & Hodgson, D. J. (1996). The relationship between power output and endurance: a brief review. European Journal of Applied Physiology and Occupational Physiology, 73, 491 - 502.

Nagata, A. (1981). EMG power spectra during various levels of isometric contraction and fatigue. Yokohama Medical Bulletin, 33, 49-64.

Norris, S. R., & Smith, D. J. (1996). Determination of the equivalent biological load for treadmill running compared to indoor track running at submaximal speed (Abstract). The Physiologist, 39 (5), 40.3.

Overend, T. J., Cunningham, D. A., Paterson, D. H., & Smith W. D. F. (1992). Physiological responses of young and elderly men to prolonged exercise at critical power. European Journal of Applied Physiology and Occupational Physiology, 64, 187-193.

Pepper, M. L., Housh, T. J., & Johnson, G. O. (1992). The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. International Journal of Sports Medicine, 13 (2), 121-124.

Peronnet, F., & Thibault, G. (1989). Mathematical analysis of running performance and world running records. Journal of Applied Physiology, 67, 453-465.

Petersen, S. R., Dressendorfer, R. H., & Stickland, M. K. (1996). Critical aerobic power during 20 km bicycle racing (Abstract).The Physiologist, 39 (5), 40.1.

Poole, D. C., Ward, S. A., & Whipp, B. J. (1990). The effects of training on the metabolic and respiratory profile of high-intensity cycle ergometer exercise. European Journal of Applied Physiology and Occupational Physiology, 59, 421-429.

Rhodes, E. C., & McKenzie, D. C. (1984). Predicting marathon time from anaerobic threshold measurements. The Physician and Sportsmedicine, 12 (1).

Scarborough, P. A., Smith, J. C., Talbert, S. M., & Hill, D. W. (1991). Time to exhaustion at the power asymptote (critical power) in men and women (Abstract).Medicine and Science in Sports and Exercise, 23, (4), 67.

Smith, D. J. (1992). Swimming performance tests. Calgary, Alberta, Canada: University of Calgary, National Swimming Sport Science Centre.

Smith, D. J., Lefort, J., & Kranenburg, K. (1994). Effect of an intense training cycle and taper on critical power, anaerobic work capacity and testosterone in trained athletes (Abstract). Canadian Journal of Applied Physiology, 19, 45P.

Smith, D. J., & Norris, S. R. (1996).Prediction of 5,000 m, 3,000 m for females and 1,500m performance from on-ice and laboratory measures in all-around speed skaters. (Abstract). The Physiologist, 39 (5), 40.5.

Smith, J. C., & Hill, D. W. (1992). Mathematical models of the power-time relationship in high intensity cycling (Abstract). Medicine and Science in Sports and Exercise, 24, (5), 443.

Smith, J. C., & Hill, D. W. (1993). Stability of parameter estimates derived from the power time relationship. Canadian Journal of Applied Physiology, 18 (1), 43-47.

Smith, J. C., Hill, D. W., & Talbert, S. M. (1991). Prediction of the power asymptote in men and women: role of repeated testing (Abstract). Medicine and Science in Sports and Exercise, 23, (4), 68.

Stegmann, H., & Kinderman, W. (1982). Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol lactate. International Journal of Sports Medicine, 3 (2), 105-110.

Talbert, S. M., Smith, J. C., Scarborough, P. A., & Hill, D. W. (1991). Relationships between the power asymptote and indices of anaerobic and aerobic power (Abstract). Medicine and Science in Sports and Exercise, 23, (4), 158.

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

Wakayoshi, K.,Yoshida, T., Kasai, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). Validity of critical velocity as swimming fatigue threshold in the competitive swimmer. Annals of Physiological Anthropology, 11 (3), 301-307.

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993).Does critical swimming velocity represent exercise intensity at maximal lactate steady state? European Journal of Applied Physiology and Occupational Physiology, 66, 90-95.

Wakayoshi, K., Yoshida, T., Udo, M., Moritani, T., Mutoh, Y., & Miyashita, M. (1992). A simple method for determining critical speed as swimming fatigue threshold in competitive swimming. International Journal of Sports Medicine, 13 (5), 367-371.

Zaryski, C. L., Smith, D. J., & Wiley, J. P. (1994). Relationship between discipline speed, individual event speed and speed during a simulated Olympic distance triathlon (Abstract). Canadian Journal of Applied Physiology, 19, 53P.

CHAPTER 3

A COMPARISON OF CRITICAL VELOCITY ESTIMATES TO ACTUAL VELOCITIES IN PREDICTING SIMULATED ROWING PERFORMANCE

Introduction

Critical Velocity has been used as a simple and inexpensive method to predict maximal average velocity in a variety of sports: swimming (Wakayoshi et al., 1992), running (Pepper, Housh & Johnson, 1992; Kachouri et al., 1996; Kranenburg & Smith, 1994) and triathlons (Zaryski, Smith & Wiley, 1994). Any application of CV concepts has been based on the simple linear relationship between total work done and time to exhaustion at that work load (Monod & Scherrer, 1965). McDowell, Kenney, Hughes, Housh, & Johnson (1988) applied the CP total work-time model to distance and time values by replacing the dependent variable (total work) with total distance (linear distance-time model). Wakayoshi et al. (1992) utilized this model for swimming and found a strong correlation ($R^2 = .999$, $p<0.01$) between distance swam and time to exhaustion in swimmers. Such a strong correlation suggested that CV was an excellent predictor of time (velocity) over a predetermined distance. As well CV has been correlated to physiological parameters including Maximal Lactate Steady State (MLSS) for swimming (Wakayoshi et al., 1993) and VO_2 max for running (Pepper et al., 1992) but may overestimate the Individual Anaerobic Threshold (IAT) (McLellan & Cheung, 1992) or MLSS (Jenkins & Quigley, 1990) when CP was utilized in cycle ergometry (Jenkins & Quigley; McLellan & Cheung). Previous research from our laboratory has found a significant difference between actual (410 seconds) and predicted (400 seconds) times for simulated rowing over 2000 metres from a critical velocity estimate based on the linear distance-time model and one set of trials (250, 500, 750, 1000 metres) (Kennedy & Bell, 1996). Other CV models include linear distance-1/time initially proposed by Hughson, Orok, & Staudt (1984) and the nonlinear velocity-time model initially proposed by Moritani, Nagata, deVries, & Muro (1981) but later modified by Pepper, Housh, & Johnson (1992) to fit distance and time parameters. Presently there has been no CV model which accurately predicts simulated rowing performance over 2000 metres.

The standard race distance for rowing is 2000 m and the energy requirements of this type of performance include having a well developed aerobic system, strength and anaerobic fitness (Secher, 1993). Mean race times for male rowers over a simulated 2000 meter race range from 6-8 minutes and at present there are few pacing strategies to predict and or enhance performance in rowers. Therefore, the purpose of this study was: **a)** to analyze the effect of different models on CV estimates, **b)** determine the main and interaction effects of CV estimates produced by 3 different CV models and 6 different trials **c)** to test the accuracy of 12 CV estimates (produced by 3 different models in combination with 4 different sets of trials) to predict 2000 meter velocity in simulated rowing and **d)** assess the relationship of CV and $\dot{V}O_2$ max in predicting 2000 meter velocity.

Methods

Subjects:

Subjects were recruited from the local rowing club and university rowing population. All subjects were male (N=16) and had a minimum of 1 year rowing experience. Subject Characteristics are provided in Table 3-1. All subjects signed a consent form prior to testing and the study had ethical approval by the Faculty of Physical Education and Recreation, University of Alberta (see Appendix D).

Critical Velocity Trials:

Critical Velocity parameter estimates, were limited to no longer than 60% of the predicted distance (2000 m) for two reasons: convention was to utilize trials no longer than 50-60 % in formation of CV estimates and trials longer than 50% have associated metabolic and fatigue factors that make the trial burdensome (Clingeleffer, McNaughton, & Davoren, 1994). The present investigation utilized a series of 6 trials. The distance of the CV trials were 200, 400, 600, 800, 1000 and 1200 metres and were randomly assigned for each subject. A 2000 metre time trial to determine actual 2000 metre velocity was also performed. Time(s), average stroke rate, split time / 500 metres and heart rate were recorded for each trial. All tests were performed on a Model C, Concept II rowing machine. The trials were spaced by a minimum of 24 hours rest to ensure maximal glycogen repletion and other associated effects of fatigue from previous trials (MacDougall, Ward, Sale, & Sutton, 1977). All trials were preceded by a 1000 metre warm-up with 3 maximal 5 second sprints included in the warmup. The subjects were required to stretch and rest for five minutes before assuming a race start position on the ergometer. The randomized time trial for each subject that day was programmed on the Concept II computer display. The subject was able to view the following information on the ergometer screen: cumulative metres, time / 500 metres, stroke rate and time.

At the completion of the trial the display recorded time to the nearest 1/ 10th of a second and mean stroke rate. The importance of giving maximal efforts in the trials was imperative to the validity of CV estimates. No verbal encouragement was given during the trials in an attempt to minimize the external factors such as cheering which may have affected performance. Subjects were asked prior to each trial to provide their best effort and treat each trial as a "race". The 2000 metre time trial occurred after completion of all the CV trials and was performed in the same manner as described above.

Critical Velocity Determination:

Each subject had 12 CV estimates formed from their trial data (200, 400, 600, 800, 1000, 1200 m). The 12 estimates were determined by the following method: 4 sets of trials in combination with 3 mathematical models to produce 12 different CV estimates (Table 3-2). Each subjects data was divided into 12 different groups so that each different CV estimate group consisted of 16 data points (i.e. the individual CV estimates determined from each subjects trial data). The statistical analysis utilized the mean of each group (i.e. all 12 CV estimates are group means).

The distance sets were:

Short (S) = 200, 400, 600, 800 metres
Medium (M) = 400, 600, 800, 1000 metres
Long (L) = 600, 800, 1000, 1200 metres
All Distances (AD) = 200, 400, 600, 800, 1000, 1200 metres

The 3 mathematical models were:

Model 1) Linear distance-time model as proposed by McDowell, Kenney, Hughes, Housh, & Johnson (1988).This model relies on the inherent principle that a line of best fit through a series of data points will continue to be linear beyond the area covered by the plotted points. Mathematically, the CV estimate was calculated using the equation:

$$\mathbf{d = CV(t) + AWC}$$

d = the dependent variable of **distance** (metres)
t = the independent or manipulated variable of **time** (seconds)
CV = the slope of the relationship between distance and time or **Critical Velocity** ($m \cdot s^{-1}$)
AWC = the y-intercept or the **Anaerobic Work Capacity** (metres)

Model 2) Linear velocity-1/time model was proposed by Hughson, Orok, & Staudt (1984). It involves the plot of velocity and the fractional component of time (1/time) to gives values which are sensitive to longer trials used in Critical Velocity determination. The equation is:

$$v = \frac{AWC}{t} + CV$$

v = **velocity** at which each trial was completed ($m \cdot s^{-1}$)

t = **time** to complete each trial (seconds)

AWC = slope of the relationship indicating **Anaerobic Work Capacity** (metres)

CV = y-intercept (**Critical Velocity**) of the relationship between velocity and 1/time ($m \cdot s^{-1}$)

Model 3) The nonlinear velocity-time model was initially proposed by Moritani, Nagata, deVries, & Muro (1981) and later modified by Pepper, Housh, & Johnson (1992) to fit distance and time parameters.

$$t = \frac{AWC}{(v-CV)}$$

t = **time** to complete each trial (seconds)

v = **velocity** at which each trial was completed ($m \cdot s^{-1}$)

AWC = slope of the relationship between velocity and time indicating **Anaerobic Work Capacity** (metres)

CV = the power asymptote or y-intercept (**Critical Velocity**) based on the relationship of time to fatigue at each trial and the velocity at which the trial was completed ($m \cdot s^{-1}$)

Determination of Aerobic Fitness Parameters:

Prior to any of the trials all subjects were required to undergo a combined incremental ventilation threshold ($\dot{V}E/\dot{V}CO_2$) and maximal oxygen consumption test to volitional exhaustion on a Concept II Model C rowing ergometer. Maximal oxygen consumption was determined by a) a peak or plateau in oxygen consumption, b) an RER> 1.1, c) volitional exhaustion (Thoden, as cited in Macdougall et al, 1991). All subjects wore a heart rate monitor (Polar Electro Heart Rate Monitors) set to measure heart rate every 5 seconds. Ventilatory and gas exchange parameters were averaged every 15 seconds (SensorMedics Horizon Metabolic cart) using open circuit spirometry. Calibration of the metabolic cart was done with known concentations of oxygen and carbon dioxide prior to and after each test. The protocol started with an initial power output of 100 watts followed by a 50 Watt increase every 2 minutes until an RER of approximately 1.05 was reached at which point the subjects were instructed to provide an all-out effort until volitional exhaustion. The testing for all subjects was spaced a minimum of two days prior to the initial CV trial. No increase in training volume or intensity above normal levels was allowed during the study.

Data Analysis:

A one way ANOVA was used to analyse any differences in CV estimates derived by the 3 different models utilizing all the trials distances. A two way ANOVA (3 x 3) determined main effects for models (3 models) and trial sets (S, M, L) as well as interaction effects between the 9 different CV values. A one way ANOVA was run to determine any statistical differences between 2000 metre velocity and CV determined using the twelve different methods. A Newman Keuls post hoc test was used for any multiple comparisons. Stepwise multiple regression was used to determine the degree of variability accounted for by maximal oxygen consumption and the most accurate CV value for prediction of 2000 metre velocity. Although Anaerobic Work Capacity values were generated they were not examined in this study. An alpha level of $p < 0.05$ was preset. All statistical analysis and CV determination were done with SPSS software (Statistical Package for Social Sciences, Version 6.1).

Results

Prediction of 2000 metre velocity was most accurate using the linear distance-time model (M1) and all 6 trial distances (AD) (actual 2000 m velocity = 4.9 (± 0.2) $m \cdot s^{-1}$; AD(M1) velocity = 4.9 (± 0.2) $m \cdot s^{-1}$). A difference was seen between model 3 (M3) and model 1 (M1) ($p<0.05$) as well as model 2 (M2) ($p<0.05$) when AD were utilized. Analysis of the 2 way ANOVA provided the following results: a) main effect for distance ($p<0.05$); b) a significant model x distance interaction effect; c) multiple comparisons revealed the following interactions were not significant: M3(L) and M1 or M2 (L), M3 (L) and M3 (M), M3(M) and M1 or M2 (L), M2 (M or L) and M1 (M or L) ($p>0.05$) (Figure 3-1). Seven CV estimates were not significantly different than 2000 metre velocity ($p>0.05$) including: M1(AD), M1(M), M2(M), M2(L), M3(S), M3(M), M3(L) (Table 3-3). The CV value with the smallest absolute difference (M1, AD) accounted for $R^2 = 0.948$, $p<0.05$ of the total variance associated with predicting 2000 metre velocity. Addition of $\dot{V}O_2$max ($l \cdot min^{-1}$) to CV produced an $R^2 = 0.962$, $p<0.05$. Table 3-4 provides a correlation matrix of Pearson r values summarizing the significant correlations between CV, 2000m velocity and selected physiological variables.

Discussion

Critical Velocity calculated using model 1 and all trial distances provided the most accurate prediction of actual 2000 m velocity (refuting the hypotheses) and accounted for approximately 95% ($R^2 = 0.948$, $p<0.05$) of the variability associated with the prediction of 2000 metre velocity. Addition of $\dot{V}O_2$ max ($l\cdot min^{-1}$) to the CV estimate provided an $R^2 = 0.962$, $p<0.05$. It was hypothesized that $\dot{V}O_2$ max would be the better predictor of 2000 metre rowing performance than CV. The strength of the relationship between $\dot{V}O_2$ max ($l\cdot min^{-1}$) and 2000m velocity is similar ($r = 0.905$) to the relationship between CV and 2000 m velocity ($r = 0.974$). It is important to note that maximal oxygen consumption (absolute) is a good indicator of rowing performance as shown by the results.

There was a main effect for distance (supporting the hypothesis) but not for CV model, although the interaction of model and distance results indicated that the type of model still may have had an effect on the outcomes of the CV parameters. The analysis of CV models (with all distances) provided a significant difference between the nonlinear model and the two linear models. It was hypothesized that type of model would be a factor in the determination of the CV estimate when all distances were utilized. Lastly it is important to note that the nonlinear model produced the two most conservative estimates (AD & L) both at 4.7 $m\cdot s^{-1}$.

A bias seemed to exist with the CV estimates produced by the nonlinear model in regard to the interaction effect, conservativeness of the CV values and accuracy for the prediction of 2000 metre velocity. The interaction effect of other model and distance combinations with the nonlinear model was primarily limited to the short trials of the nonlinear model. Each model (1, 2, or 3) had interactions occur between different trial lengths within the same model except the nonlinear model which had no interaction between medium and long trials (i.e. M3{M} ↔ M3{L}). As well analysis determined that the medium and long distances within model 3 were not significantly influenced by long trials in either model 1 or model 2 (see Figure 3-1). This would indicate that the nonlinear model had inherent external (not influenced by other model-distance combinations as much as model 1 or 2) and internal validity (there was no interaction between model 3 (long) and model 3 (medium)). Hill, Smith, Leuschel, Chasteen, & Miller (1995), stated that there was no main effect for regression model (same mathematical models as this investigation) but that there was a significant difference between the linear models and the nonlinear model at 2 of the 3 different cadence methodologies (similar to the distance variable in this investigation) utilized in their study. Our results found a main effect for distance but not for model as well, which lends support to the nonlinear models ability to provide accurate estimates regardless of the set of distances used (the exception being model 3 and all distances which provided a significantly different estimate from 2000 metre velocity). It is worthy to note that the Hill et al. (1995) investigation found the nonlinear estimates to be the most conservative regardless of the cadence methodology used. Gaesser, Carnevale, Garfinkel, Walter, & Womack (1995) asserted that the nonlinear model (3 parameter or 2 parameter) produced the most conservative CP estimate and that nonlinear regression provided the best goodness of fit for the trial data. The same nonlinear model used in the Hill et al. and Gaesser et al. (1995) investigations produced estimates for short, medium, and long distances which were not significantly different from 2000 metre velocity in this research investigation. Therefore supporting previous research, this investigation found the application of the nonlinear model to "CV estimation" does not diminish its ability to provide the most conservative, stable and accurate CV estimate.

Numerous research investigations have utilized 4 trials (Carnevale & Gaesser, 1991; Florence & Weir, 1997; Housh, Housh, & Bauge, 1990) or less than 4 trials (Bishop & Jenkins, 1996; Clingeleffer, Mc Naughton, & Davoren, 1994) to determine CV or CP estimates. The use of 6 trials in our investigation was necessary for 2 reasons; to determine whether 6 data points improved the accuracy of the prediction as well as it allowed for the trials to be manipulated into different length sets (short, medium & long). This allowed an analysis to be made as to the effect of different trial lengths on the CV estimate. In defence of the 6 trial methodology, model 1 in conjunction with all 6 trials did provide the most accurate prediction of 2000 metre velocity. Analysis of the trials in the different length sets (S, M, L), determined that medium set of distances (400, 600, 800, 1000m) with either model 1, 2, or 3 provided estimates with no significant difference from actual 2000 metre velocity. The medium combination of distances on the basis of accuracy was therefore found to be the best set of distances for prediction of 2000 metre velocity. It is important to note that the addition of the 2 extra data points (to form the all distance set) did not improve the overall accuracy of all distances versus medium distances to predict 2000 metre velocity. Therefore the results indicate that the medium distance set and the nonlinear model are preferred.

Nonlinear models are preferred but may not be the best model to use from a sport performance perspective. If the critical velocity concept is to take hold in the coaching and sport performance testing areas the process by which the CV estimate is derived must be accurate but simple to create. Nonlinear modelling requires estimates to be performed on a computer equipped with a statistical package capable of performing nonlinear regression as well as a coach or tester who is familiar with nonlinear regression. All of this adds to the impracticality of utilizing the nonlinear model in non research oriented applications of critical velocity. The present research finds the linear 1/time model and the linear distance time models produced similar estimates to the nonlinear model when the medium set of distance was used (Table 3-3). If accuracy is not compromised the linear regression models are certainly more practical to the coach in a field testing situation (i.e. a calculator and detailed instructions would suffice in producing the CV estimate).

Conclusions

Results indicated that the preferred CV model and distance set overall in simulated rowing is the medium distance (regardless of the model used) and the nonlinear model (regardless of the distance used). As well both CV and maximal oxygen consumption provide similarly significant correlations to 2000 m velocity. From a research perspective the non linear model has the most inherent validity but, the nonlinear model lacks practicality in the sport performance area. Therefore the linear models are suggested as a similarly accurate option to nonlinear regression. Future steps in validation of CV estimation for predictive purposes include the reliability of CV estimates based on single tests at each trial distance and application of these findings to open water rowing.

REFERENCES

Bishop, D., & Jenkins, D. G. (1996). The influence of resistance training on the critical power function and time to fatigue at critical power. The Australian Journal of Science and Medicine in Sport, 28 (4), 101-105.

Carnevale, T. J., & Gaesser, G. A. (1991). Effects of pedalling speed on the power-duration relationship for high-intensity exercise. Medicine and Science in Sports and Exercise, 23 (2), 242-246.

Clingeleffer, A., McNaughton, L. R., & Davoren, B. (1994). Critical power may be determined from two tests in elite kayakers. European Journal of Applied Physiology and Occupational Physiology, 68, 36-40.

Florence, S., & Weir, J. P. (1997). Relationship of critical velocity to marathon running performance. European Journal of Applied Physiology and Occupational Physiology, 75, 274 - 278.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., Walter, D. O., & Womack, C. J. (1995). Estimation of critical power with nonlinear and linear models. Medicine and Science in Sports and Exercise, 27 (10), 1430-1438.

Hill, D. W., Smith, J. C., Leuschel, J. L., Chasteen, S. D., & Miller, S. A. (1995). Effect of pedal cadence on parameters of the hyperbolic power -time relationship. International Journal of Sports Medicine, 16 (2), 82-87.

Housh, D. J., Housh, T. J., & Bauge, S. M. (1990). A methodological consideration for the determination of critical power and anaerobic work capacity. Research Quarterly for Exercise and Sport, 61 (4), 406- 409.

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A high velocity treadmill running test to assess endurance running potential. International Journal of Sports Medicine, 5, 23-25.

Jenkins, D. G., & Quigley, B. M. (1990). Blood lactate in trained cyclists during cycle ergometry at critical power. European Journal of Applied Physiology and Occupational Physiology, 61, 278- 283.

Kachouri, M., Vandewalle, H., Billat, V., Huet, M., Thomaidis, M., Jousselin, E., & Monod, H. (1996). Critical velocity of continuous and intermittent running exercise: An example of the limits of the critical power concept. European Journal of Applied Physiology, 73, 484-487.

Kennedy, M., & Bell, G. (1996). Prediction of 2000 metre rowing times using critical velocity parameter estimates (Abstract). The Physiologist, 39 (5), 40.8.

Kranenburg, K., & Smith, D. J. (1994). Prediction of 9.8 km performance in elite runners using critical speed (Abstract). Canadian Journal of Applied Physiology, 19, 24P.

MacDougall, J. D., Ward, G. R., Sale, D. G., & Sutton, J. R. (1977). Muscle glycogen repletion after high intensity intermittent exercise. Journal of Applied Physiology, 42, 129-132.

McDowell, S. L., Kenney, K. B., Hughes, R. A., Housh, T. J., & Johnson G. J. (1988). The relationship between ventilatory threshold and critical velocity. Abstracts of the Research Presentations at the National AAPHERD Convention, AAPHERD Publications.

McLellan, T. M., & Cheung, K. Y. (1992). A comparative evaluation of the individual anaerobic threshold and the critical power. Medicine and Science in Sports and Exercise, 24 (5), 543-550.

Monod, H., & Scherrer, J. (1965). The work capacity of synergic muscle groups. Ergonomics, 8, 329-338.

Moritani, T. A., Nagata, H. A., deVries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24, 339-350.

Pepper, M. L., Housh, T. J., & Johnson, G. O. (1992). The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. International Journal of Sports Medicine, 13 (2), 121-124.

Secher, N. (1993). Physiological and biomechanical aspects of rowing: Implications for training. Sports Medicine, 15, 24-42.

Smith, J. C., & Hill, D. W. (1993). Stability of parameter estimates derived from the power time relationship. Canadian Journal of Applied Physiology, 18 (1), 43-47.

Smith, J. C., Hill, D. W., & Talbert, S. M. (1991). Prediction of the power asymptote in men and women: role of repeated testing (Abstract). Medicine and Science in Sports and Exercise, 23, (4), 68.

Thoden, J. (1991). In J. D. Mac Dougall et al. (Ed.), Physiological Testing of the High Performance Athlete. Champaign , Illinois: Human Kinetics.

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

Wakayoshi, K., Yoshida, T., Udo, M., Harada, T., Moritani, T., Mutoh, Y., & Miyashita, M. (1993).Does critical swimming velocity represent exercise intensity at maximal lactate steady state? European Journal of Applied Physiology and Occupational Physiology, 66, 90-95.

Zaryski, C. L., Smith, D. J., & Wiley, J. P. (1994). Relationship between discipline speed, individual event speed and speed during a simulated Olympic distance triathlon (Abstract). Canadian Journal of Applied Physiology, 19, 53P.

Table 3-1: Subject characteristics

Age (yr)	**Height (cm)**	**Weight (kg)**	**$\dot{V}O_2$ max (l·min^{-1})**	**$\dot{V}O_2$ max (ml·kg^{-1}·min^{-1})**	**VT -1 (l·min^{-1})**	**VT - 2 (l·min^{-1})**
22.7 ± 3.9	186.2 ± 6.5	83.7 ± 8.4	5.01 ± 0.50	59.9 ± 6.1	2.42 ± 0.43	3.58 ± 0.66

Values are means ± S.D. (N = 16)

Table 3-2: Experimental design

	MODEL 1	**MODEL 2**	**MODEL 3**
SHORT TRIALS	CV1	CV2	CV3
MEDIUM TRIALS	CV4	CV5	CV6
LONG TRIALS	CV7	CV8	CV9
ALL DISTANCES	CV10	CV11	CV12

Table 3-3: Comparison of all critical velocity estimates to actual 2000 metre velocity

	Short Distance	**Medium Distance**	**Long Distance**	**All Distance**
Model 1	5.1 ± 0.2 m·s^{-1}	***4.9 ± 0.3 m·s^{-1}**	4.8 ± 0.3 m·s^{-1}	***4.9 ± 0.2 m·s^{-1}**
Model 2	5.3 ± 0.2 m·s^{-1}	***5.0 ● 0.3 m·s^{-1}**	***4.8 ● 0.3 m·s^{-1}**	5.1± 0.2 m·s^{-1}
Model 3	***5.0 ± 0.3 m·s^{-1}**	***4.8 ● 0.2 m·s^{-1}**	***4.7 ± 0.2 m·s^{-1}**	4.7 ± 0.3 m·s^{-1}

Note: Actual 2000 metre velocity = 4.9 m·s^{-1}

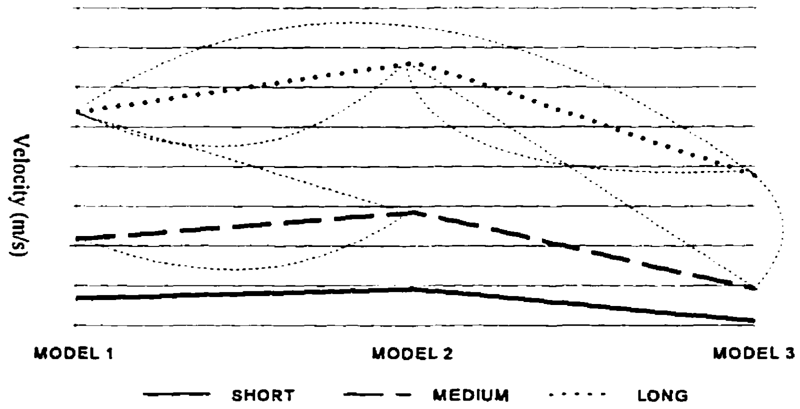
* denotes no significant difference between 2000 metre velocity and CV estimate

Table 3-4: Correlation matrix for critical velocity, 2000 m velocity and selected physiological variables

	Critical velocity	**Maximal oxygen consumption (abs)**	**Maximal oxygen consumption (rel)**	**2000 m velocity**
Critical velocity		*0.905	*0.611	*0.974
Maximal oxygen consumption (abs)	*0.905		*0.511	*0.932
Maximal oxygen consumption (rel)	*0.611	0.511		*0.504
2000 m velocity	*0.974	*0.932	*0.504	

*$p<0.05$

Values are Pearson product moment coefficient of correlation



Faint dashed lines = not significant interactions

Figure 3-1: Interaction of model x distance

CHAPTER 4

GENERAL DISCUSSION AND CONCLUSIONS

Hypotheses And Results:

The investigation had two major purposes; to validate different models and distance of trials used in the CV function for simulated rowing performance and to determine the most accurate model-distance combination for prediction of 2000 metre velocity in simulated rowing. The experimental design included:

1) analysing the CV estimates created by all distances using the 3 mathematical CV models to determine the effect that the model had on the CV parameters independent of the distance variable.
2) calculate the main and interaction effects between CV model and distance (S, M, L with M1, M2, M3).
3) identification of which CV estimates were not statistically different from actual 2000 metre velocity.
4) define the relationship between the most accurate CV estimate, maximal oxygen consumption and actual 2000 metre velocity.

The hypotheses for the different questions included in order:

1) All models would produce significantly different values.
2) There would be main effects for models and trials and a significant interaction effect would occur.
3) The most accurate model-distance combination would be long trial and model 2 (linear velocity-1/time).
4) Maximal oxygen consumption would be the best predictor of 2000 metre velocity.

For validation purposes it was important to determine whether different models gave significantly different estimates. The nonlinear model provided a significantly different value compared to both the linear models as well as the most conservative CV estimate (4.7 $m \cdot s^{-1}$ versus 4.9 $m \cdot s^{-1}$ (M1) & (M2) 5.1 $m \cdot s^{-1}$). The significant difference between CV models implies that the choice of CV model has an effect on the estimation of performance. Previous research has utilized only one model (Bulbulian, Wilcox, & Darabos, 1986; Carnevale & Gaesser, 1991; Florence & Weir, 1997; Housh, Housh, & Bauge, 1989; Pepper, Housh, & Johnson, 1992). Few articles have purposefully compared different models in an attempt to validate CV or CP estimates (Gaesser, Carnevale, Garfinkel, Walter, & Womack, 1995; Hill, Smith, Leuschel, Chasteen, & Miller, 1995; Hopkins, Edmond, Hamilton, MacFarlane, & Ross, 1989). Future research should utilize different models to elicit the CV estimates in the experimental design, ensuring the most accurate prediction of the target performance. Contrary to the present results, the hypothesis stated that there would be significant differences between all models. However, there was no difference between the linear models. Possible reasons for this finding may be that models utilized the same basic distance and time values in a linear fashion. The difference is that the velocity -1/time model fractionalizes both time and distance to produce its working x and y coordinates (y = distance/time or {velocity} & x = 1/time (see Appendix C). As well, the same 6 distances were used in the models, therefore the distance variable had little influence on the outcome of the CV estimate (i.e. linear velocity -1/time model is particularly sensitive to changes in distance). Further analysis of the results determined that model 1 and model 2 both have 2 CV estimates which are not significantly different from 2000 metre velocity . Therefore it is difficult to differentiate between the 2 linear models on a statistical level. It is therefore important to look at the individual differences between the 2 models before a conclusion may be drawn as to which linear model is preferred. The linear distance-time model produces the single best estimate of 2000 metre velocity (with all distances) but the linear velocity-1/time provided its 2 best estimates from distance sets that are shorter in length (medium and long distance sets) than the linear distance-time model. From a practical perspective, accurate estimates based on shorter trials is more important than a CV estimate with perfect accuracy. It is important to note that the linear distance-time model also utilized all 6 trials to form the most accurate estimate versus the velocity- 1/time model which used 4 data points. Therefore the linear distance-1/time model was the better linear model because it provided accurate estimates with shorter trials.

It was also hypothesized that both distance and model would have a main effect. The results indicate a main effect for distance but not for model. There were numerous interactions between model and distance which did support the hypothesis that an interaction between CV model and distance set would occur. The observed interaction effects provide valuable information as to what model and distance combinations were most robust (i.e. influenced the least by other CV model-distance combinations). These interactions are summarized in Appendix A. The results of the two way ANOVA illustrate that of the 72 possible interactions only 7 were not significant. These 7 not significant interactions are the important clues to the CV model-distance set relationship. Most important is the fact that medium or long distance sets were involved in all of the interactions which were not significant. A summary of not significant interactions is provided in Table 4-1. Therefore from a methodological perspective, because it was determined that the shorter duration medium trials provide similarly robust estimates as the long trials, the medium trials would be preferred for two reasons: less time required to perform the trials and reduced fatigue from performing each trial.

The analysis of 2000 metre velocity and the 12 CV estimates as well produced some corroborating evidence to support medium distance sets. The one way ANOVA for 2000 metre velocity and CV estimates produced 7 CV's that were similar (refer to Table 3-3). Medium distances in conjunction with each of the 3 models were not significantly different from 2000 metre velocity. Critical Velocity methodology relies on the premise that the trials used to form the parameter estimate are short and not associated with excessive fatigue. The shorter the trial, the lower the residual fatigue the athlete experiences and consequently the medium trials should be endorsed as the better set of distances. It was hypothesized that model 2 (L) would be the most accurate parameter but the CV estimate with the smallest difference was Model 1 (AD) when compared to actual 2000 metre velocity (0.016 $m \cdot s^{-1}$ for Model 1 (AD) with Model 2(M) differing by 0.019 $m \cdot s^{-1}$). The medium distance in this instance utilized 2 less trials to form the estimate (than AD) and still produced an extremely accurate value (i.e. 0.003 difference between M2(M) and the most accurate CV estimate M1(L)).

The CV model that most accurately predicted 2000 metre velocity was Model 3, which produced 3 estimates (S, M, L) that were not significantly different from 2000 metre velocity. The best model overall from an accuracy standpoint was model 3. Model 1 and model 2 both had 2 CV estimates that were not significantly different from 2000 metre velocity. Therefore, the most accurate predictor of 2000 metre velocity was achieved with the nonlinear model and medium distance. Despite this finding, the practicality of this combination can be questioned for a variety of reasons. If the present CV theories are to be continually applied to real world sport performance settings the nonlinear model would not be the chosen CV model. As previously mentioned, a nonlinear CV model requires extensive calculation and data analysis to produce an asymptote value based on the plot of velocity versus time. The majority of coaches, athletes and applied exercise physiologists would not have access to such a program in a field setting. Therefore, the nonlinear CV model would not be practical. The linear models on the other hand may be computed with a calculator and drawn on graph paper. The medium distance set for this investigation utilized 4 data points all rowed at maximal effort (400, 600, 800, and 1000 metres). This distance set had mean times ranging from 69.4 ± 2.8 s (400m) to 192.4 ● 9.7 s (1000m). Critical velocity estimation requires an **"all out effort"** to increase the reliability of the testing procedure. If the CV estimates are used to gauge or monitor performance over a period of time, and multiple trials by an individual are being performed at each distance then the reproducibility of the trial is an important issue. The best way to standardize the intensity of each trial over a period of time is to have the athlete perform them at maximal intensity. Anecdotally it was reported by a number of subjects that the ability to perform maximally at distances greater than 1000 metres (3 minutes) was difficult. Therefore, a pacing strategy was required by the subjects to produce the best time for the longer trials distances. This would indicate that the 1000 m distance may be too long to provide reliable data for the formation of the CV estimate. The medium distances (400, 600, and 800 metres) may prove to be more reliable and not as demanding on the subjects. The elimination of one data point from a non linear model may skew the line of best fit and contribute to standard error (Morton & Hodgson, 1996). Linear models will produce different parameter estimates than a nonlinear model on the basis of how the data is calculated in each respective model as stated by

Colquhoun (cited in Gaesser, Carnevale, Garfinkel, Walter, & Womack, 1995). Clingeleffer, Mc Naughton, & Davoren (1994) found that 2 data points gave similarly accurate CV estimates as 4 data points with a linear distance-time model. Previous research (Gaesser et al., 1995) indicates that if a linear model is used for practical reasons and 3 data points are used to form that estimate, then the linear models should give a more accurate CV estimate than the mathematically equivalent nonlinear model . Therefore it is the contention of the author that in applied physiology, CV estimation for rowing should utilize 3 distances ranging in time from 1 minute to 2.5 minutes plotted with a linear model.

There are significant and similar correlations between 2000 m velocity and both maximal oxygen consumption (absolute) and CV. Therefore it is difficult to distinguish whether or not maximal oxygen consumption or CV is the better predictor of rowing performance. The hypotheses purported that maximal oxygen consumption would be the best predictor, and this was not supported by the results. CV estimation does not require the laboratory time or equipment that aerobic fitness testing does. As well CV estimation may be easily arranged in a training schedule and could potentially be used as a tool to indicate changes in performance over a training period.

Critical Velocity Theory and Applications:

Since the first published report on critical power, there have been a few basic premises which all researchers have utilized as well as questioned. The idea that our muscular function may be linked to a critical intensity which if surpassed provides only a finite amount of energy for muscular work has been the basis for all critical power and critical velocity investigations (Moritani, Nagata, deVries, & Muro, 1981). Whether this ideal is manipulated for other purposes including prediction of performance times (velocity), monitoring of training progress or a marker of performance, the basic similarities still exist. Most research has occurred in closed environments with consistent conditions (Hill, 1996; Overend, Cunningham, Paterson, & Smith, 1992; Smith & Hill, 1993). The application of critical velocity to outdoor sports has met with some success for running (Kranenburg & Smith, 1994; McDermott, Forbes, & Hill, 1993) and for triathlons (Zaryski, Smith, & Wiley, 1994). The multi event sport of triathlons is comprised of swimming, cycling and running legs, therefore in essence CV estimation has been used in swimming and cycling as well. Such research lends support to the application of CV concepts to open water rowing.

The application of CV theory to open water rowing is best suited to the individual rowing events. A proposed method to determine CV parameter estimates for open water rowing would include performing the CV trials indoors on a rowing machine. The estimate could then be applied to the open water considering that the shells would need to be equipped with a speedometer reporting a constant average velocity (Speedcoach Inc.), allowing the predetermined CV estimate to be adhered to. In theory, maximal average velocity would be attained based on the athlete's fitness at the time of the race. It is important to remember that due to the maximal effort involved in CV trials the elite athlete is best suited to this type of testing.

Critical velocity theory may also be used as a method to quantify (CV could determine the amount of work done) and regulate intensity (train at a specified velocity) in training programs. The popular heart rate training method (where athletes train at predetermined heart rates for their workouts) is based on the single physiological variable, heart rate. Heart rate is subject to variability from many factors not related to fitness or performance. The CV concept is based on performance (a product of fitness, technique, psychology, emotional well being) allowing the intensity to be based on the performance of the individual and not a singular physiological parameter such as heart rate.

Due its performance based attributes CV maybe better suited to team camps and team selection than other more traditional methods of determining performance (for example: maximal oxygen consumption). CV theory utilizes all aspects of the athlete's ability therefore the CV value could provide a truer perspective and a more accurate standard as to how each athlete is performing.

Conclusions:

The present investigation has provided both descriptive and empirical data about simulated rowing performance and the concept of critical velocity. Prediction of rowing velocity over 2000 metres was best predicted using a nonlinear model and a set of distances in the 400 - 1000 metre range. A set of 3 trials from 400 - 800 metres in conjunction with a linear CV model is recommended for previously mentioned reasons. Knowledge and use of CV in rowing would be useful for pacing strategy in simulated rowing, monitoring of fitness changes and as a method to quantify training volume.

Future Directions and Comparisons:

The application of CV theory has been used in swimming (Hill, Steward, & Lane, 1995; Wakayoshi et al., 1992) and could be potentially well used in the sports of speed skating, track and field, track cycling, and rowing. CV can also provide a method for quantification of training volume. The sport of road cycling could benefit from this application. Serious road cycling requires a great time commitment and the tendency for cyclists to do too much or too little training can be a factor in the success of the athlete. Most long rides (4 hours or greater) are conducted at very low heart rates with the independent variable as time. The dependent variable, distance is a product of the intensity at which the athlete cycles and can be regulated by heart rate. The advent of on-board cycle computers equipped with watts now allows the cyclist to view their power output (critical power). The velocity of a cyclist can be regulated by the amount of muscular work involved in turning the pedal cranks which in turn rotates the wheel. Velocity can change greatly when a hill or a headwind is experienced. The velocity drops and the cyclists must apply a greater force on the pedals to maintain the average velocity. This extra expenditure of energy leads to fluctuations in heart rate and the rider eventually becomes more fatigued than if he had not tried to maintain his velocity. If CP were used instead of velocity to regulate intensity, when a stressor like a hill is experienced the work output can be maintained at a constant rate because the energy production is being regulated not the product of the work (velocity). This would allow cyclists to predetermine their energy expenditure for a workout and provide extremely accurate training data (quantified by the athletes energy output). This CP application could be applied to rowing as well, especially in the off-season where Canadian rowers train on rowing machines equipped with power output.

Our results are similar to other research investigation when the purpose of the study was prediction of a performance time or velocity. Over 10, 000 metres running there was no significant difference between race speed and the CV estimate (Kranenburg & Smith, 1994) or predicted race time (minutes) and the CV estimate (McDermott, Forbes, & Hill, 1993). Zaryski, Smith, & Wiley (1994) found CV underestimated the event speed for swimming but overestimated CV as it related to the cycling and running legs of an Olympic distance triathlon. Our investigation found 5 CV estimates overestimated actual velocity over 2000 m, 5 CV estimates underestimated actual velocity over 2000 m, and 2 CV estimates provided the same velocity as 2000 m velocity.

REFERENCES

Bulbulian, R., Wilcox, A. R., & Darabos, B. L. (1986). Anaerobic contribution to distance running performance of trained cross-country athletes. Medicine and Science in Sports and Exercise, 18 (1), 107-113.

Carnevale, T. J., & Gaesser, G. A. (1991). Effects of pedalling speed on the power-duration relationship for high-intensity exercise. Medicine and Science in Sports and Exercise, 23 (2), 242-246.

Clingeleffer, A., McNaughton, L. R., & Davoren, B. (1994). Critical power may be determined from two tests in elite kayakers. European Journal of Applied Physiology and Occupational Physiology, 68, 36-40.

Florence, S., & Weir, J. P. (1997). Relationship of critical velocity to marathon running performance. European Journal of Applied Physiology and Occupational Physiology, 75, 274 - 278.

Gaesser, G. A., Carnevale, T. J., Garfinkel, A., Walter, D. O., & Womack, C. J. (1995). Estimation of critical power with nonlinear and linear models. Medicine and Science in Sport and Exercise, 27 (10), 1430-1438.

Hill, D. W. (1996). Determination of accumulated O_2 deficit in exhaustive short-duration exercise. Canadian Journal of Applied Physiology, 21(1), 63 - 74.

Hill, D. W., Smith, J. C., Leuschel, J. L., Chasteen, S. D., & Miller, S. A. (1995). Effect of pedal cadence on parameters of the hyperbolic power -time relationship. International Journal of Sports Medicine, 16 (2), 82-87.

Hill, D. W., Steward, R. P., & Lane, C. J. (1995). Application of the critical power concept to young swimmers. Pediatric Exercise Science, 7, 281-293.

Hopkins, W. G., Edmond, I. M., Hamilton, B. H., Macfarlane, D. J., & Ross, B. H. (1989). Relation between power and endurance for treadmill running of short duration. Ergonomics, 32 (12), 1565-1571.

Housh, D. J., Housh, T. J., & Bauge, S. M. (1989). The accuracy of the critical power test for predicting time to exhaustion during cycle ergometry. Ergonomics, 32 (8), 997-1004.

Kranenburg, K., & Smith, D. J. (1994). Prediction of 9.8 km performance in elite runners using critical speed (Abstract). Canadian Journal of Applied Physiology, 19, 24P.

McDermott, K. S., Forbes, M. R., & Hill, D. W. (1993). Application of the critical power concept to outdoor running (Abstract). Medicine and Science in Sports and Exercise, 25 (5), 610.

Moritani, T. A., Nagata, H. A., deVries, H. A., & Muro, M. (1981). Critical power as a measure of physical work capacity and anaerobic threshold. Ergonomics, 24, 339-350.

Morton, R. H., & Hodgson, D. J. (1996). The relationship between power output and endurance: a brief review. European Journal of Applied Physiology and Occupational Physiology, 73, 491 - 502.

Overend, T. J., Cunningham, D. A., Paterson, D. H., & Smith W. D. F. (1992). Physiological responses of young and elderly men to prolonged exercise at critical power. European Journal of Applied Physiology and Occupational Physiology, 64, 187-193.

Pepper, M. L., Housh, T. J., & Johnson, G. O. (1992). The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. International Journal of Sports Medicine, 13 (2), 121-124.

Smith, J. C., & Hill, D. W. (1993). Stability of parameter estimates derived from the power time relationship. Canadian Journal of Applied Physiology, 18 (1), 43-47.

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

Zaryski, C. L., Smith, D. J., & Wiley, J. P. (1994). Relationship between discipline speed, individual event speed and speed during a simulated Olympic distance triathlon (Abstract). Canadian Journal of Applied Physiology, 19, 53P.

Table 4-1: Not significant interactions for model-distance combinations

	Model 2 (M)	Model 2 (L)	Model 3 (M)	**Model 3 (L)**
Model 1 (M)	*			
Model 1 (L)		*	*	*
Model 2 (L)			*	*
Model 3 (M)				*

APPENDIX A

INTERACTIONS FOR MODEL AND DISTANCE

	M1 (S)	M1(M)	M1(L)	M2(S)	M2(M)	M2(L)	M3(S)	M3(M)	M3(L)
M1(S)		0.000144	0.000121	0.000313	0.000106	0.000118	0.000118	0.000122	0.000117
M1(M)	0.000144		0.000210	0.000118	0.052565	0.000299	0.000137	0.000423	0.000118
M1(L)	0.000121	0.000210		0.000117	0.000118	0.748664	0.000122	0.565668	0.112767
M2(S)	0.000313	0.000118	0.000117		0.000144	0.000122	0.000106	0.000121	0.000134
M2(M)	0.000106	0.052565	0.000118	0.000144		0.000106	0.009110	0.000144	0.000122
M2(L)	0.000118	0.000299	0.748664	0.000122	0.000106		0.000144	0.881560	0.099306
M3(S)	0.000118	0.000137	0.000122	0.000106	0.009110	0.000144		0.000118	0.000121
M3(M)	0.000122	0.000423	0.565668	0.000121	0.000144	0.881560	0.000118		0.080440
M3(L)	0.000117	0.000118	0.112767	0.000134	0.000122	0.099306	0.000121	0.080440	

White Cells = $p<0.05$
Shaded Cells = $p>0.05$

APPENDIX B

VENTILATORY THRESHOLDS ($l \cdot min^{-1}$)

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	MEAN
VT1	2.17	2.66	2.66	3.34	2.74	2.67	2.36	2.66	1.93	3.52	2.56	2.03	1.92	1.96	1.94	2.52	2.42 ± 0.42
VT2	3.53	3.14	3.76	4.86	3.95	3.25	4.14	3.40	2.49	4.75	3.88	3.40	2.50	3.29	3.24	3.83	3.59 ± 0.66
VT1 (%VO_2 max)	40.6	59.2	63.0	58.8	52.9	49.1	42.9	53.5	46.2	63.5	52.7	37.2	42.2	43.1	35.5	52.6	49.6 ± 8.9
VT2 (%VO_2 max)	66.1	69.9	89.1	85.6	76.3	59.7	75.2	68.4	59.6	85.7	79.8	62.3	54.9	72.3	59.2	80.0	71.5 ± 10.7

S1 = Subject 1

The purpose of this appendix was to summarize the ventilation threshold data obtained from the combined ventilation threshold/maximal oxygen consumption test. The rationale for doing this is that ventilation thresholds have been shown to be highly related to performance in endurance events (MacDougall et al., 1977). Threshold 1 was determined as the lowest point using the ventilatory equivalent for oxygen consumption (V_E/VO_2) versus power output relationship that corresponded with the lowest point for F_EO_2. Threshold 2 was determined as the lowest point for the ventilatory equivalent for carbon dioxide production (V_E/VO_2) versus power output relationship that corresponded to the highest point for F_ECO_2 (Bhambhani and Singh, 1985). Detailed methodology for the exercise protocol has been previously expained in the thesis. This information will be used to investigate further relationships between critical velocity parameters, maximal oxygen consumption and performance during a simulated 2000 meter indoor rowing race.

Bhambhani, Y & Singh, M. (1985). Ventilatory threshold during a graded exercise test. Respiration, 47, 120-128.

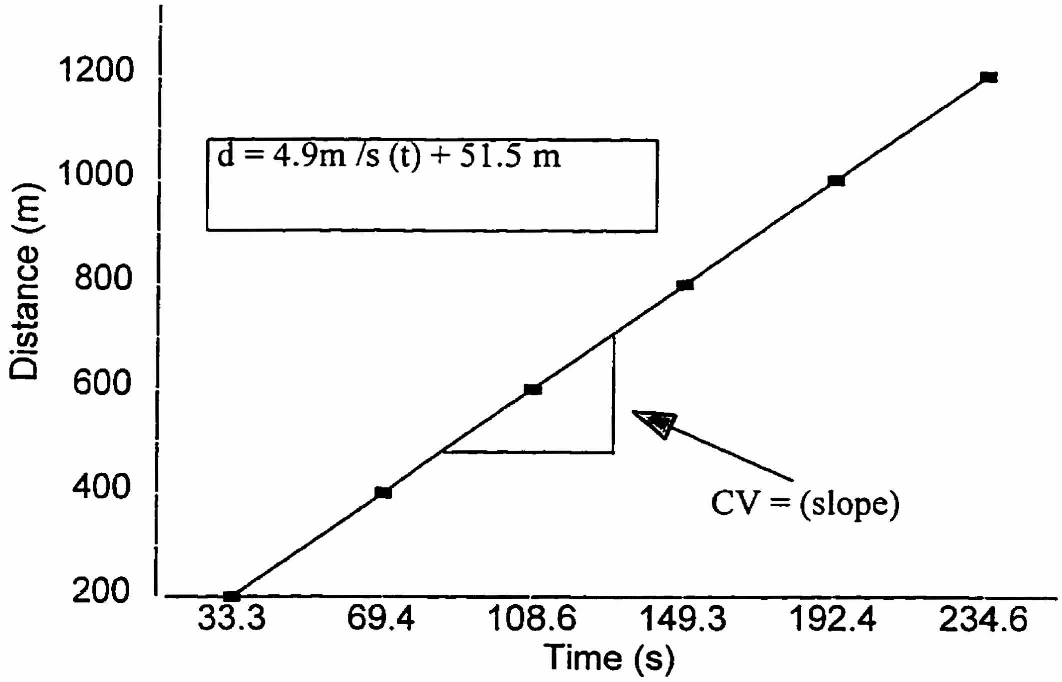
MacDougall, D. (1977). The anaerobic threshold: Its significance for the endurance athlete. Canadian Journal of Applied Sport Science, 2, 137-140.

APPENDIX C

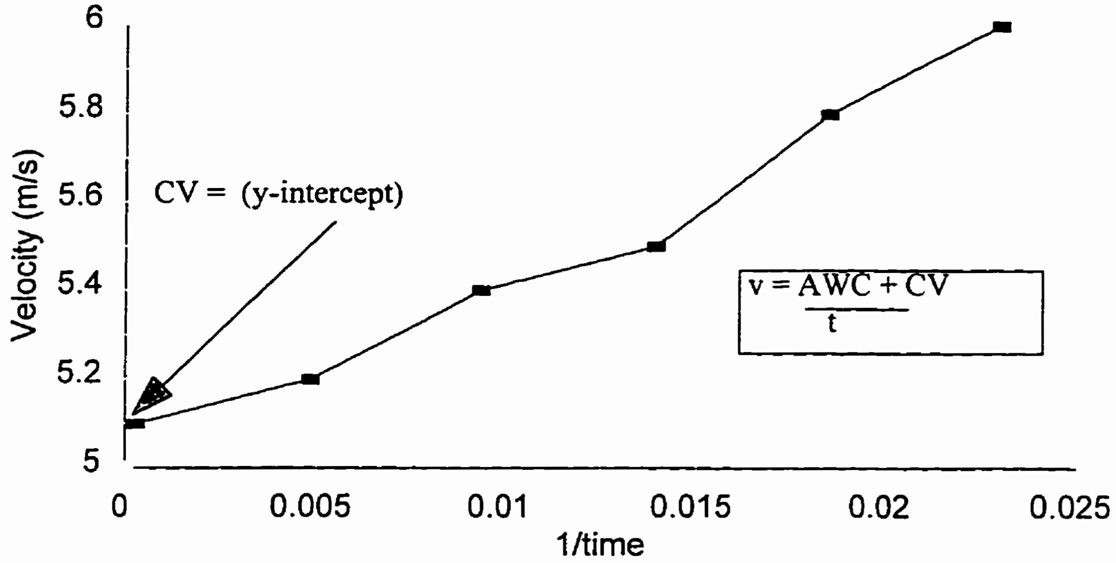
CRITICAL VELOCITY DETERMINATION (ALL SUBJECTS)

Distance (m)	Time (s)	1/Time	Velocity(m/s)
200m	33.3	0.0301	6.0
400m	69.4	0.0144	5.8
600m	108.6	0.0092	5.5
800m	149.3	0.0067	5.4
1000m	1192.4	0.0052	5.2
1200m	234.6	0.0043	5.1

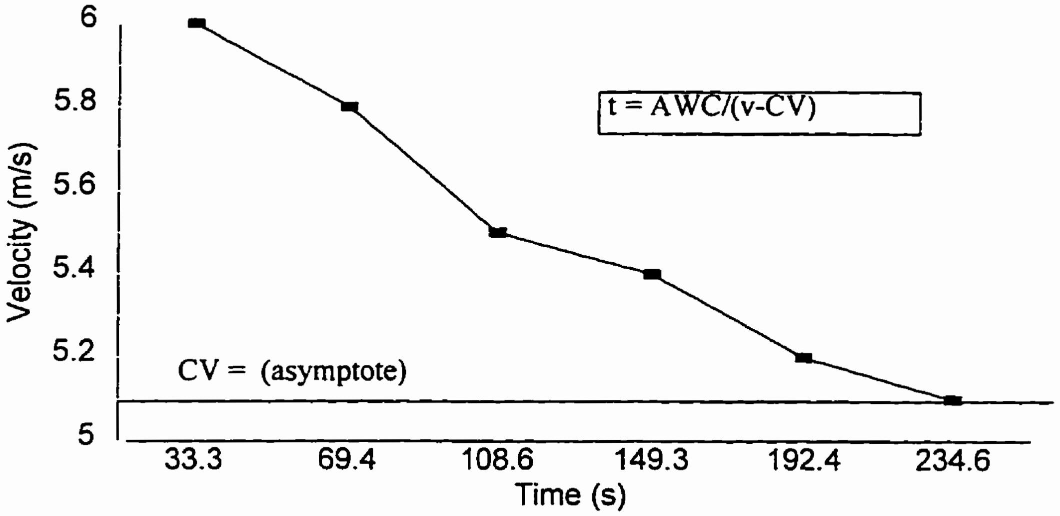
*Model 1 as an example has the derived equation determined from all distances.



Model 1: Linear Distance-Time



Model 2: Linear Velocity-1/Time



Model 3: Non Linear Velocity-Time

APPENDIX D

*Informed consent approved by the Faculty of Physical Education and Recreation Ethics Review Committee

A Comparison of Critical Velocity Estimates to Actual Velocities for Prediction of Simulated Rowing Performance

Investigators:

Michael Kennedy	465-9384	Faculty of Physical Education and Recreation
Gordon Bell	492-2018	Faculty of Physical Education and Recreation

INFORMED CONSENT FOR EXERCISE TESTING AND TRAINING

I,_______________ (Please print your name) agree to participate in a research project conducted by the above named investigators studying the nature of critical velocity in rowing. I agree to participate in the exercise testing procedures to the best of my ability. I understand that I may withdraw from the study at any time without reason, or discontinue any test procedure without any consequence. I also understand that the staff conducting the test will discontinue any procedures if any indications of abnormal responses become apparent. I understand that prior to performing any test listed below I will have the opportunity to question and discuss the exact procedures to be followed.

Physiological Assessments:

1. Anthropometry - measurement of height and weight.
2. Ventilation Threshold (VT) and $\dot{V}O_2$ max - a continuous 12 minute exercise test of increasing intensity to exhaustion on a rowing machine while monitoring metabolic responses and heart rate.
3. Simulated rowing races of randomly assigned distances 200, 400, 600, 800, 1000 and 1200 metres (as well as a 2000 metre time trial) to determine time (seconds) for each trial rowed - splits (/500 metres)and stroke rate will be measured during each test.

   Testing will occur on different days and the distance of the of the simulated race will be randomly assigned and will involve 7 separate visits for the rowers that will vary in time per visit depending on the test.

Time Commitment:

Testing will occur within a 3 week period and will involve 7 separate visits to perform the rowing trials. As well the subjects will all perform the VT and $\dot{V}O_2$ max on a separate day from the rowing trials. A conservative estimate for all testing and rowing trials would be 6-10 hours. A minimum of 24 hours between visits would be required between visits to perform any of the trials.

Risks:

The exercise tests will require maximal physical and mental effort. However, the effort required will not be greater than that experienced during sport performance. They represent little risk to healthy, active individuals involved in sport.

Consent:

I acknowledge that I have read this form and I understand the test procedures to be performed and the inherent risks and benefits involved from the participation in this project. I consent to participate understanding that I may withdraw at any time. I may expect a copy of this consent form at the time of signature and a report of my personal results after the study is complete and that the data collected will be used in a research publication and will always remain in possession of the investigator to ensure confidentiality and anonymity. I also understand that I may make enquires concerning any procedure that I do not completely understand.

Name:____________________________ Signature:_________________________________

Address:____________________________ Date:____________________

____

Postal Code:____________ Phone:______________________ Age:________________

Witness:__________________________ Investigator:___________________________