

PREDICTION OF TRIATHLON PERFORMANCE FROM
VENTILATORY THRESHOLD MEASUREMENTS

by

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ABSTRACT

The purpose of this study was to predict Ironman Triathlon (2.4 mile swim, 112 mile cycle, 26.2 mile run) performance times from ventilatory threshold (T_{VENT}) measurements of swimming, cycling, and running. Ten trained triathletes (mean age = 29.7yrs., ht = 179.8cm, wt = 76.8kg, bodyfat = 11.4%) performed progressive intensity tests for treadmill running, cycle ergometry, and tethered swimming. The excess CO_2 elimination curve was used to determine T_{VENT} in each component sport with the resulting estimated times of 64.2, 380.0, 174.5, 672.8 minutes for swimming, cycling, running, and overall time respectively. Individual estimates were then compared to actual segment and overall times to produce the following linear regression equations for predicting actual from estimated time (in minutes):

$$\text{actual swim} = 1.15 * \text{estimated swim} - 6.75$$

$$\text{actual cycle} = 0.22 * \text{estimated cycle} + 262.6$$

$$\text{actual run} = 3.03 * \text{estimated run} - 267.1$$

$$\text{actual overall} = (-3.58 * \text{est. swim}) + (-0.10 * \text{est. cycle}) + (3.76 * \text{est. run}) + 291.35$$

Significant correlations of $r = 0.83, 0.70, 0.76$, and 0.89 were calculated between swim, cycle, run, and overall estimated versus actual times respectively. Thus, between 49 and 69% of the variance in actual time is explained by T_{VENT} for that component sport. Also, 78% of the total variability was accounted for by the T_{VENT} estimation when the three sports were combined. These findings suggest that while T_{VENT} is able to account for a significant proportion of triathlon performance time other factors such as fatigue, dehydration, terrain, heat, etc. are confounding the overall prediction.

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CHAPTER 1

1.1 Introduction to the Problem

Over the years many attempts have been made to describe the factors which limit the ability to perform prolonged endurance exercise. Studies have attempted to identify the physiological variables that are the most important determinants of endurance performance. Among the key variables that have been shown to be significantly related to performance of endurance activities are: maximal oxygen uptake ($\dot{V}O_{2MAX}$), economy of motion, fractional utilization of $\dot{V}O_{2MAX}$ ($\% \dot{V}O_{2MAX}$), anaerobic threshold, and fuel supply (Sjodin and Svedenhag, 1985).

Early research (Owles, 1930; Harrison and Pilcher, 1930) supported the existence of critical levels of work intensity above which there was accumulation of blood lactate with accompanying increases in CO_2 excretion and ventilation. This critical intensity was termed the "anaerobic threshold" and defined the workrate at which the tissues oxygen supply first fell below demand and excess energy needs were supported by anaerobic metabolism (Wasserman and McIlroy, 1964). In theory, below this point work may be performed for indefinite durations since the energy requirements are being supplied predominantly through unlimited aerobic energy sources, while waste products are being adequately removed (Anderson and Rhodes, 1989). In order to best define the anaerobic threshold point both noninvasive and invasive variables such as \dot{V}_E , $\dot{V}_E/\dot{V}O_2$, $\dot{V}CO_2$, excess CO_2 , and blood lactate have all been monitored with varying degrees of success. Particular emphasis has been placed on the refinement of noninvasive respiratory variables in order to minimize the need for invasive procedures. This has allowed researchers to use progressive workload

increases to bring about nonlinear responses in respiratory exchange variables to noninvasively define anaerobic threshold.

While the nomenclature and mechanisms inherent in the anaerobic threshold concept are still being challenged, there is widespread support particularly in the performance data. The threshold appears to represent a key parameter defining the ability to maintain high intensity exercise (Whipp et al., 1981) and a critical intensity level above which endurance performance is severely limited (Rhodes and McKenzie, 1984). It is suggested that exercise intensity at anaerobic threshold represents a maximal steady state level that an athlete can sustain for an extended period without accumulating lactate.

Anaerobic threshold related variables have been shown to have a close relationship to endurance performance that is good or better than other physiological variables including $\dot{V}O_{2\text{MAX}}$ (Tanaka et al., 1981; Davis et al., 1979). Several performance studies have documented the value of anaerobic threshold as a determinant of endurance activities. Studies of long distance running produced correlations of the order of 0.88 to 0.99 for distances ranging from 3.2 km to the marathon (Conconi et al., 1982; Farrell et al., 1979; Powers et al., 1983; Sjodin and Schele, 1982; Williams and Nute, 1983). Rhodes and McKenzie (1984) extended the concept of anaerobic threshold by instead of just correlating it with performance used treadmill running velocity at the anaerobic threshold to estimate actual marathon time with an $r=0.94$. While results have been strongest in running, other sports have shown some support. Miller et al. (1985) found anaerobic threshold to have a strong relationship ($r=0.93$) to 15 km time trial cycling performance. As well, Loat and Rhodes (1991) found the anaerobic threshold, as defined by excess CO_2 , to be a workload that could be sustained for one hour on a cycle ergometer. All of these represent situations

where anaerobic threshold has been correlated with some success to performance in single sport endurance contests.

The triathlon is an endurance contest in which participants compete consecutively in three sports, usually swimming, cycling, and running. The endurance triathlon has really only existed since 1978 when the Waikiki Rough Water Swim (3.9 km), the Around Oahu Bike Race (180.2 km), and the Honolulu Marathon (42.2 km) were combined into the Hawaii Ironman Triathlon (O'Toole et al., 1989). The three sport performance dictates that the successful triathlete is one who has the ability to perform each sequential event at optimal pace without creating fatigue that will hinder performance in the next event. While the physiological bases for success in the triathlon remain to be clarified it will obviously include the ability to maintain minimal alterations in homeostasis of cardiovascular, haemodynamic, thermal and metabolic function for long periods of time (O'Toole et al., 1989). The triathlete will seek to perform at a level optimizing potential for the duration of the event.

Studies have demonstrated evidence that in single sport contests (particularly strong in running) anaerobic threshold can be used to represent this point of optimal pace for endurance sports. Since the triathlon is an endurance contest by nature it seems reasonable that those factors which contribute to success in single event endurance contests should also contribute to triathlon success. Thus, the concept of anaerobic threshold should be able to be applied here in order to characterize performance just as in other endurance contests. At this point very few studies have looked at using ventilatory threshold as an indicator of success in triathloning.

1.2 Statement of the Problem

The purpose of this investigation was to determine if triathlon performance times can be predicted from ventilatory threshold measurements of swimming, cycling, and running.

1.2.1 Subproblems

- 1) to determine if the velocity at ventilatory threshold during running, cycling, and swimming can estimate race pace (time) for that component of the triathlon.
- 2) to determine if each component can be used together to predict overall triathlon time.

1.3 Definitions

- 1) Ventilatory threshold - (T_{VENT}) the point where the aerobic energy response is of insufficient magnitude to supply the tissues energy requirement and there is an increased reliance on anaerobic processes with an accompanying abrupt increase in excess CO_2 .
- 2) Maximal Steady State - the highest intensity work may be performed at for theoretically indefinite durations.
- 3) Excess CO_2 - nonmetabolic CO_2 ($EXCO_2$) formed as a result of the hydrogen ions of lactic acid being buffered by bicarbonate in the following reactions:



(Wasserman et al., 1973)

The calculation of excess CO_2 will be based on the formula of Volkov et al. (1975) where:

$$\text{ExCO}_2 = \dot{V}\text{CO}_2 - (\text{RQ}_{\text{rest}} * \dot{V}\text{O}_2)$$

1.4 Delimitations

This study was delimited by:

- 1) a sample of triathletes from the Vancouver area between the ages of 18 and 35 years with a minimum of two triathlons experience.
- 2) a respiratory gas sampling rate set at 15 second intervals.
- 3) the methodology applied to determine velocity at T_{VENT} for swimming, cycling, and running.

1.5 Limitations

This study was limited by:

- 1) the data collection capabilities of the Beckman Metabolic Measurement Cart and the Hewlett Packard Data Acquisition system interfaced with it.
- 2) the individuals metabolic response to the exercise protocols.
- 3) race day conditions (terrain, weather, equipment problems, etc.)

1.6 General Hypothesis

Predicted time for the triathlon will correlate highly with actual triathlon performance time. Specifically, a highly significant relationship will exist between:

- 1) treadmill run velocity at T_{VENT} and the run section of the triathlon.
- 2) tethered swim velocity at T_{VENT} and the swim section of the triathlon.
- 3) cycle ergometry velocity at T_{VENT} and the cycle section of the triathlon.

1.6.1 Secondary hypotheses

- 1) a significant difference will exist between $\dot{V}O_{2MAX}$ measured for swimming, cycling, and running such that:

$$\dot{V}O_{2MAX} \text{ run} > \dot{V}O_{2MAX} \text{ cycle} > \dot{V}O_{2MAX} \text{ swim}$$

- 2) T_{VENT} measured for swimming, cycling, and running will demonstrate the following:

- a) T_{VENT} absolute (expressed as a $\dot{V}O_2$) will show a significant difference for each component as follows:

$$T_{VENT} \text{ run} > T_{VENT} \text{ cycle} > T_{VENT} \text{ swim}$$

- b) T_{VENT} relative (expressed as a $\% \dot{V}O_{2MAX}$) will demonstrate a nonsignificant difference between each component sport when expressed as a percentage of maximum.

3) the relative heart rate at T_{VENT} (expressed as a $\%HR_{MAX}$) will also show a nonsignificant difference between the three component sports of the triathlon.

1.7 Rationale

Velocity at T_{VENT} has been used with success ($r=0.94$) in running by Rhodes and McKenzie (1984). Farrell et al. (1979) observed that runners set a race pace which closely approximates the running velocity at which lactate begins to accumulate in the plasma. These observations both support the hypothesis of a velocity which optimizes pace and minimizes fatigue (maximal steady state). Since the physiological basis for success is similar in other endurance sports it seems likely that this concept could be extended.

The relationship between $\dot{V}O_{2MAX}$ in swimming, cycling, and running is documented in the literature. Mean $\dot{V}O_{2MAX}$ values have been reported as follows:

treadmill run	cycle ergometry	tethered swim	
60.5	57.9	52.5	Kohrt et al. (1987a)
57.4	54.4	46.8	Kohrt et al. (1987b)

Thus, cycling maximums represent about 4% less and swimming maximums represent about 15% less than those achieved running on the treadmill. From these results it is expected that the absolute T_{VENT} in each component will also show the same pattern. However, when T_{VENT} is expressed in relative terms it is expected that there will no longer be differences. This is supported by the work of Schneider et al. (1990) where a nonsignificant difference was found between

T_{VENT} 's expressed as a % $\dot{V}O_{2MAX}$ for cycle ergometry and treadmill running. Relative heart rate at T_{VENT} is also expected to show this same nonsignificant difference for each component sport. Roalstad et al. (1987) reported during the Hawaii Ironman Triathlon that subjects maintained average heart rates of approximately 75% of their maximal heart rates during the bike and run portions of the race. They also observed that the better finishing times were found in those triathletes where heart rates fluctuated least over the course of the event.

1.8 Significance of the Study

If indeed ventilatory threshold defines a "critical intensity", then exercise at workloads greater than this should result in a progressive metabolic acidosis that becomes rate-limiting. Exercise time to exhaustion (duration) should have an inverse relationship to the amount exercise workrate (intensity) exceeds T_{VENT} . It is important to determine if the protocols employed in this experiment actually do define a maximal steady state at which an athlete can perform. Most endurance athletes regardless of endurance ability wish to perform for prolonged periods of time without factors such as lactate accumulation limiting performance (maximal steady state). If it can be shown that T_{VENT} does characterize this point of maximal performance it will have profound implications for the endurance athlete. It could be used in exercise prescription to select a training intensity which elicits maximal aerobic performance. There could also be application to evaluation of training over time based on T_{VENT} changes.

This study is also significant in that it takes the concepts of T_{VENT} to a performance level. Thresholds are often stated to be indicative of maximal endurance ability without actual validation. This study validates its statements about the T_{VENT} by actually testing the theories in an endurance setting

(triathlon). The use of threshold concepts outside of the lab setting is the truest test of these measures. An endurance triathlon will definitely test the ability of T_{VENT} to characterize maximal steady state during prolonged sport.

CHAPTER 2

2.0 Literature Review

2.1 Introduction

Endurance sports have been a very popular area of research for physiologists in the past few decades. This is undoubtedly due to the opportunity to observe a variety of factors under highly demanding conditions and thereby gain a better understanding of human performance potential. Much of this research in endurance capacity is designed so that a better idea of those factors contributing to success in endurance contests will emerge. As such, this would help the physiologist to develop methods for predicting performance. The notion of predicting performance success is very attractive, but is a complicated and multifaceted question encompassing areas of physiology, biomechanics, morphology, psychological profile, etc. (Toussaint and Beek, 1992). A new series of questions emerge with the advent of the multiple sport contest of triathlon, particularly with respect to the relationships between the component sports. Research, to date, is conflicting but several lines of evidence suggest a similar physiological basis that may allow prediction as has been attempted in single contest endurance sports. This review will concentrate on the physiological determinants of endurance performance in the emerging research area of triathlon by examining current findings in this sport and its component sports of swimming, cycling, and running.

2.1.1 Single Endurance Sports

There is little information concerning the aerobic capacity of competitive endurance cyclists and swimmers, in contrast to the wealth of data on endurance

runners. While swimmers tend to train comparable distance to endurance athletes (Costill et al., 1991) the majority of competitive swim events tend to be sprint oriented contests lasting less than 3 minutes (Smith et al., 1984). Consequently, most of the research has focussed on maximal performance as opposed to sustained performance.

By virtue of the man-machine interaction (Kyle and Mastropaolo, 1978), cycling research has been confined more to biomechanical considerations of cadence, seat height, gear ratios, etc. It is unquestionably running where the majority of performance research has been done. This is likely the result of cycling and swimming having much greater biomechanical components while running is more physiological (Sjodin and Svedenhag, 1985).

Lack of research should not be taken to mean a lack of evidence for the ability to determine endurance performance success in these sports. While often there are few direct correlation studies, the sports exhibit characteristics supporting the likelihood of these concepts.

2.1.2 Triathlon

While many sports have developed ultraendurance contests, triathlon is a sport created specifically to test endurance ability (O'Toole and Douglas, 1989). As a contest the Ironman triathlon, with its 2.4 mile swim, 112 mile cycle and 26.2 mile run, is synonymous with ultraendurance performance. There has been an exponential rise in popularity from only 15 starters in the first Ironman (1978) to 1275 starters in 1988 (selected from over 20,000 applicants) (O'Toole and Douglas, 1989). This rise in popularity has promoted an increased interest within the scientific community, now focussed on examining the physiological consequences of multisport training and racing. O'Toole et al. (1989) state that success in a triathlon depends upon the ability of the triathlete to perform each

of the sequential events at optimal pace without creating fatigue that will hinder performance in the next event. A heterogeneous group of Ironman triathletes maintained average heart rates of approximately 75% of maximum during the bike and run portions (Roalstad et al., 1987). Those with heart rates fluctuating least over the course of the event had the best finishing times suggesting that there is an optimal, sustainable pace that the triathlete will want to approximate to be successful. This suggests the key determinants of endurance performance, characterizing multisport endurance, may be similar to single sport endurance.

2.2 Single vs. Multiple Mode Sport

2.2.1 Specificity of training

It is the above statement of O'Toole et al. (1989) regarding "not creating fatigue that will hinder the next sequential event" that is a key factor differentiating multiple from single endurance sports. This suggests a new series of considerations that must be made to apply performance research to triathlon. The theory of training specificity suggests that adaptations to training are specific to the mode of training (Kohrt et al., 1987a). An activity is required to tax the metabolic pathways of choice (aerobic vs. anaerobic) and must also stress (or recruit) specific muscle groups and neural pathways used in the activity (Kohrt et al., 1989). Single sports necessitate adaptation to only one mode while the triathlete will need to reflect, to some degree, the specificity seen in each component sport. Clausen et al. (1973) postulated that there were both central adaptations (resulting from nonspecific training) and peripheral adaptations (resulting from training specific to the muscle groups used). Muscles used in swimming are different from those used in cycling and running, and while there is some overlap of muscle usage in cycling and running the range of motion,

recruitment patterns, length of muscles, type of contraction (concentric vs. eccentric) and speed of contraction are different (O'Toole et al., 1989). Thus, while all component sports are aerobic in nature they utilize different muscle groups (or the same muscles differently) to perform the necessary movement patterns of swimming, cycling, and running. Cycle and swim training result in improvements specific to that activity (Kohrt et al., 1987a) and produce more of a localized muscle stress and peripheral adaptations in the muscles. Magel et al. (1978) states exercise using large muscle groups (eg: running) stresses the oxygen transport mechanisms, while exercise involving smaller muscle groups (eg: swimming) tends to stress oxygen utilization. Much of the specificity of swimming is thought to relate to the reduction in active muscle mass coupled with the reduction of antigravity work while in water, and the horizontal exercise position.

Central to multisport training is the question of whether there is an ability to transfer benefits from one activity to another with the concurrent ("crosstraining") training done by triathletes. Both swim training (Magel et al., 1978) and cycle training (Pechar et al., 1974; Town and Sinning, 1982) have failed to demonstrate improvements in running ability. As well, run training has failed to demonstrate improvements in swim ability (McArdle et al., 1978). Running to improve cycling is not as definitive with some studies (Pechar et al., 1974; Town and Sinning, 1982) showing an improvement indicative of a generalized effect from run training, although this improvement tended to be quite small, suggesting only a small generalizable training effect. The work of Kohrt et al. (1987b) is the only study demonstrating a possible crosstraining effect by reducing training in cycling and swimming while maintaining run levels. At the end of a three month training phase, there was a reduction in both running

and cycling $\dot{V}O_{2\text{MAX}}$, while swimming was maintained. It is therefore possible that swim $\dot{V}O_{2\text{MAX}}$ was maintained by a generalized training effect from the other two component sports.

2.2.2 Intrinsic and Extrinsic Factors

While physiological variables govern performance to some degree, there are undoubtedly other factors that must be considered to be reducing the ability of the triathlete to maintain a constant pace. Many of the factors are present in single endurance sports, but by virtue of the increased duration these factors are more definitive "controllers of pace" in ultraendurance triathlons. To gain an understanding of the importance of these factors we only need to look at the reasons people require medical attention at the Hawaii Ironman. The primarily diagnosed reasons are dehydration (52%), exhaustion (20%), trauma (13%), heat cramps (6%) and electrolyte imbalance (5%) (Laird, 1989). Undoubtedly, many participants will show combinations of these, not single problems. The Ironman distance triathlon, by virtue of its competition time, is directly related to many of these medical problems experienced. Climate, season of the year, and topography of the course provide extrinsic factors that can magnify the medical problems. From the point of view of reduction in pace, there are few problems with the swim unless it is in a body of water where waves, current, and cold water temperature are prevalent. The most often cited problem in the bike portion is cramping due to the time on the bike (Laird, 1989). Some athletes have also cited mild dehydration at this point (Farber et al., 1991). It is during the run where problems start to become severe. The cumulative effects of time, distance, and heat begin to be manifested in dehydration, exhaustion, and electrolyte imbalances (Laird, 1989).

In events over four hours electrolyte imbalance and dehydration are suggested to be important factors in race performance (Hiller, 1989). van Rensburg et al. (1986) reported a decrease in body weight of 4.5% in a triathlon with mean finish time of 11.45 hours. Costill and Miller (1980) noted that work performance decreases and physiological indices of stress increase when even low levels of dehydration are combined with heat. This effect is magnified if there is a concomitant salt depletion. Heat cramps are often associated with this hyponatremia (Hiller, 1989). Costill and Miller (1980) estimated a 5-7% total body sodium chloride deficit in an endurance athlete sustaining a 5.8% body weight loss. Even with a modest sweat rate, combined with the heat of the Hawaii Ironman, there could be a loss of 36g of salt from the total body sodium stores of about 125g (Hiller, 1989). The solution considering that 70% of hyponatremic athletes are also dehydrated is to ensure a recommended supplemental sodium intake combined with programmed hydration (Hiller, 1989). The exact protocols remain to be investigated.

Available evidence on substrate utilization during prolonged exercise supports an increase in fat metabolism (O'Toole et al., 1989). Free fatty acid increases have been reported of between 2.9 and 4.6 times prerace values in ultraendurance triathlons (Holly et al., 1986; Van Rensburg et al., 1986). The actual use and regulation of substrates appears to be similar to other endurance activities, although there is evidence ultraendurance athletes competing for 9-16 hours may find standard rates of carbohydrate replacement to be insufficient to sustain this duration of exercise (Applegate, 1989). As well, the bike portion of the triathlon combines liquid and solid carbohydrate feedings in order to replace energy. Often carbohydrate replacement, particularly solid food, is stopped about one hour prior to the start of the run (O'Toole et al., 1989).

2.2.3 Cumulative Effects

While these intrinsic factors will play a role in performance the cumulative effects of performing three endurance events in their own right sequentially will bring about changes in body physiology that must be dealt with. The study of Kreider et al. (1988) compared single sport performances to equivalent component sport performances in a triathlon. One of the main differences observed in the cycling was the increase in core temperature during swimming causing thermoregulatory and cardiovascular responses to occur earlier in triathlon cycling. These responses were similar to changes found in the latter stages of the control cycling session. The subjects were unable to maintain control cycling work rates as the triathlon cycling session progressed. Possibly this decrease in performance was due to thermal stress and/or the early signs of dehydration. The cumulative effects were even more evident in the run. The post cycling core temperature was 38.4°C versus an initial control run core temperature of 37°C. The subjects perceived the work during the triathlon run to reflect increased physiological stress. A further 1.5% loss of body weight occurred during the run and while core temperature and dehydration responses were not excessive, the thermal stress would only be magnified during actual race environmental conditions. Therefore, triathletes should frequently take in fluids to minimize elevation in core temperature, dehydration, and impaired performance (Kreider et al., 1988).

2.3 Physiological Determinants of Endurance Performance

While many variables have been examined relative to endurance performance three key physiological ones have been the focus of research:

- 1) economy of motion

2) maximal aerobic power ($\dot{V}O_{2\text{MAX}}$)

3) anaerobic threshold (Pate and Branch, 1992).

Each has been demonstrated to be a determinant of endurance performance, characterizing the ability of an athlete to sustain effort for prolonged periods.

Economy refers to the rate of energy expenditure associated with a given rate of power output or speed of movement (Pate and Branch, 1992). This will be desirable to the endurance athlete given that being "economical" will result in a lesser rate of energy expenditure, thus conserving energy to help sustain performance. Maximal aerobic power ($\dot{V}O_{2\text{MAX}}$) represents the upper rate limit of one's ability to use oxygen in metabolism. High performance capacity has been strongly linked to this peak of aerobic metabolism (Sjodin and Svedenhag, 1985). Finally, the anaerobic threshold defines a workload intensity at which blood levels of lactic acid begin to rise significantly above normal resting values (MacDougall, 1977). In the simplest sense this is the point of imbalance between lactic acid production and its removal or uptake beyond which progressively more lactate accumulates in the blood. The association of lactate accumulation with fatigue suggests anaerobic threshold represents the peak of the body's ability to perform prolonged exercise. Each of these measures has demonstrated characteristics necessary for endurance success in several sports.

2.3.1 Maximal Aerobic Power

Since the athlete wishes to develop an ability to perform at the maximal sustainable oxygen consumption, early studies focused on $\dot{V}O_{2\text{MAX}}$ as the source of relationships.

2.3.1a Swimming

The economical use of energy which would be a prerequisite for distance swimming success is of less importance over short distances (Holmer, 1974). As most swim contests are short duration, the swimmer's selection of the optimal combination of local muscle power and endurance will tend to favour power at the expense of endurance (Craig and Pendergast, 1979). Thus, most of the predictive research has focused on generating maximal energy output without much regard to the ability to sustain performance long term. Considering this it is not surprising that the majority of correlations of swim performance have been to $\dot{V}O_{2MAX}$. Several researchers (Chatard et al., 1985; Costill et al., 1985; Montpetit et al., 1981) have found high correlations between $\dot{V}O_{2MAX}$ and performance. Chatard et al. (1990) found 368m swim performance mainly related to $\dot{V}O_{2MAX}$ ($r=0.80$). Costill et al. (1985) and Nomura (1983) also found high correlations of the order of $r=0.80$ and $r=0.75$ respectively between swim performance and $\dot{V}O_{2MAX}$. The observation by LePere and Porter (1975) that $\dot{V}O_{2MAX}$ is greater in more skilled swimmers suggest it could be used to differentiate performance success. Often in endurance settings the measure of $\dot{V}O_{2MAX}$ is modified to better represent the actual level of performance and is called the fractional utilization of $\dot{V}O_{2MAX}$ ($\% \dot{V}O_{2MAX}$). Magel et al. (1975) used a fractional utilization of 70% of maximum determined in a swimming $\dot{V}O_{2MAX}$ test as the basis of training and was able to improve swim performance. Holmer (1974) found at a similar workrate of 60-70% $\dot{V}O_{2MAX}$ blood lactate levels were not significantly elevated, suggesting an ability for prolonged performance at this level.

2.3.1b Cycling

Cycling has rarely been examined with $\dot{V}O_{2\text{MAX}}$ as the criterion measure to predict performance. Krebs et al. (1986) found $\dot{V}O_{2\text{MAX}}$ to be the most significant physiological predictor related to 25 mile time trial cycling. Malhotra et al. (1984) studying performance time in an 84km cycling event found the highest correlation ($r=-0.87$) with $\dot{V}O_{2\text{MAX}}$. In examining time to exhaustion, Aunola et al. (1990) found that 70% of the variance could be explained by the workrate performed at maximum.

2.3.1c Running

$\dot{V}O_{2\text{MAX}}$ is a sensitive indicator of level of marathon running ability (Sjodin and Svedenhag, 1985) and race pace ($r>0.78$) (Foster et al., 1977; Farrell et al., 1979; Maughan and Leiper, 1983). It is not only marathons that have produced high correlations with $r=0.76$ and $r=0.97$ for 10 km by Williams and Cavanagh (1987) and Morgan and Martin (1986) respectively. In addition, running research has also examined the velocity at $\dot{V}O_{2\text{MAX}}$ as a predictor variable and it was found to have a significant relationship ($r=0.87$) with 10 km race time (Sjodin and Svedenhag, 1985).

2.3.1d Triathlon

Maximal aerobic power has been found to range from no significant relationship to Ironman performance in cycling ($r=0.04$) (O'Toole et al., 1987) to a significant relationship ($r=-0.78$) (Kohrt et al., 1987a). A similar result is seen in the run with no relationship ($r=-0.09$) (O'Toole et al., 1987) to a moderate relationship ($r=-0.68$) (Kohrt et al., 1987a). Peak $\dot{V}O_2$ in tethered swimming correlated ($r=-0.50$) with swim times to produce no significant relationship (Kohrt

et al., 1987a). van Rensburg et al. (1984) found correlations of $r=-0.52$ for cycling and $r=-0.58$ for running. As well, relationships between $\dot{V}O_{2MAX}$ and performance times were found for swimming ($r=-0.49$), cycling ($r=-0.32$) and running ($r=-0.55$) in the study of Dengel et al. (1989).

2.3.1e Concerns

Although $\dot{V}O_{2MAX}$ has demonstrated success as a predictor of performance there are situations where its usefulness is severely reduced. $\dot{V}O_{2MAX}$ has a very low relationship to performance in more homogeneous samples of athlete. Despite heart rate and lactate data reflecting that swimmers were improving endurance, this did not imply equivalent changes in $\dot{V}O_{2MAX}$ (Costill et al., 1991). Acevedo and Goldfarb (1989) found run times improved without changes in $\dot{V}O_{2MAX}$ suggesting it may not be the best indicator of endurance performance. When a subgroup of runners with more similar performance capabilities were studied, there was a nonsignificant correlation ($r=0.08$) between marathon performance and $\dot{V}O_{2MAX}$ (Costill, 1972). He speculated that it was possible for two runners to have identical $\dot{V}O_{2MAX}$ values but differ drastically in their ability to utilize a large fraction of that capacity. Furthermore, relatively low $\dot{V}O_{2MAX}$ values have been found in some elite marathoners (Costill et al., 1976; Costill et al., 1973). Thus, while having a high maximal oxygen uptake is of great importance it does not equal success and other factors must be able to compensate for a low capacity.

2.3.2 Economy of Motion

Svedenhag and Sjodin (1985) found enhancement in running performance, occurring after $\dot{V}O_{2MAX}$ had reached a plateau, to be associated with slow, steady improvement in economy. There is a paucity of economy of motion studies from a physiological point of view, most focus on more biomechanical aspects.

2.3.2a Swimming

Often physiological economy of motion has been successful because of its ability to, in some way, represent technical ability factors. Such is the case with swim economy which has been shown to be a good predictor of technical ability (Pendergast et al., 1977) and a prerequisite for success in performance (van Hardel, 1988). Often, it is these technical ability factors (stroke length, stroke rate, etc.) that are controlling performance (to some degree) and have been shown to have a moderate to high relationship with free swimming (Jensen and Tihanyi, 1978). Economy, expressed as high efficiency for swimming strokes, is a vital prerequisite to the maintenance of a high velocity over long distances (Holmer, 1974). As well, diPrampo et al. (1974) and McArdle (1971) observed that even highly proficient swimmers have considerable variation in the energy cost to swim at a given speed.

2.3.2b Cycling

Athletic performance velocity during cycling is determined by the highest steady-state rate of oxygen consumption that can be tolerated and the biomechanical economy of motion, defined as the velocity achieved for a given oxygen consumption (Coyle et al., 1988). While efficiency is clearly important,

physiological economy of motion has not been measured in a performance sense.

2.3.2c Running

The variation in submaximal oxygen requirements of running at a specific speed is indicative of differences in economy between subjects (Costill et al., 1973; Sjodin and Schele, 1982; Daniels, 1974). It is with this observation in mind that economy of motion has received considerable attention for studying running. Running economy, defined as the steady-state oxygen consumption for a given running speed, has been shown to account for a large and significant proportion of the variation in distance running performance among runners roughly comparable in $\dot{V}O_{2\text{MAX}}$ (Morgan, 1989; Morgan et al., 1989). In athletes with a similar $\dot{V}O_{2\text{MAX}}$, Conley and Krahenbuhl (1980) and Morgan and Craib (1992) found running economy to significantly correlate with 10 km time ($r=0.79$ to 0.83). Daniels (1974) recognized the ability of economy to account for nearly identical 2 mile run times among two champion male runners. Costill and Winrow (1970) state different performance ability in two runners with similar $\dot{V}O_{2\text{MAX}}$ values could be attributed to individual differences in economy.

2.3.2d Triathlon

Despite its obvious importance very little triathlon research has focused on economy. Roalstad (1989) found economy at a work rate of 160W to significantly relate ($r=0.61$) to bike finish time. Dengel et al. (1989) reported submaximal $\dot{V}O_2$ measured in each mode to be related to swim ($r=0.72$), cycle ($r=0.60$), and run ($r=0.64$) times. A correlation of $r=0.78$ between cycle ergometry and bike finish time in a half Ironman triathlon was also demonstrated (Dengel et

al., 1986). O'Toole et al. (1989) reported a relationship ($r=0.61$) between percent peak $\dot{V}O_2$ at 160W and bike finish time.

2.3.2e Concerns

Running economy has been found to exhibit the same problem as $\dot{V}O_{2\text{MAX}}$ when a narrower subgroup of runners with similar performances in marathon are studied (Davies and Thompson, 1979). Daniels et al. (1984) found individual stability in run economy varied by as much as 11% within a particular test period. The relationship between run economy and level of training is equivocal, some studies showing worse economy in untrained and moderately trained (nonelite) runners and other studies demonstrating no difference between trained and untrained (Morgan and Craib, 1992). Relationships of running economy with distance running are not always high, ranging from $r=0.36$ (Foster et al., 1977) to $r=0.83$ (Conley and Krahenbuhl, 1980). Most studies involving economy provide little rationale with respect to the chosen level for performance measurements. Considerable concern is raised by Pate et al. (1992) where it was observed that running economy tended to be poorer in subjects with higher maximal aerobic power. This may suggest an artifact in the specific testing protocols used in some studies with respect to the chosen speed for measurement. If a speed is chosen to be submaximal for all athletes, those with the highest $\dot{V}O_{2\text{MAX}}$ will be at a very low relative percentage of $\dot{V}O_{2\text{MAX}}$, probably appreciably lower than their typical training intensity (Pate et al., 1992). Thus, runners at lower $\dot{V}O_{2\text{MAX}}$ values may have trained more frequently at running velocities similar to those used in the investigation and were more mechanically efficient at those velocities (Bailey and Pate, 1991). The high $\dot{V}O_{2\text{MAX}}$ runners may have been uncomfortable trying to perform at the prescribed level and a

subsequent reduction in economy was found. Consequently, faster runners may be uneconomical at speeds that are slower than their race pace (Williams and Cavanagh, 1987).

2.3.3 Anaerobic Threshold

Considering endurance performance, the anaerobic threshold has been described as a key parameter which defines the ability to sustain high-intensity exercise (Caiozzo et al., 1982).

2.3.3a Swimming

Anaerobic threshold studies done in swimming have been geared to setting training intensities for athletes in the pool. The observation that the energy expenditure rate increases exponentially with velocity (Holmer, 1979) suggests an optimal point for endurance performance. Olbrecht et al. (1985) found that the speed swum for 30 and 60 minutes was nonsignificantly different from lactate threshold (T_{LAC}) predicted speed. Further, the lactic acid concentration at the end of 30 minutes of swimming was similar ($p > 0.05$) to lactic acid concentration at T_{LAC} . In swimmers with similar $\dot{V}O_{2MAX}$ values anaerobic threshold has demonstrated an ability to differentiate performance capacity (Smith et al., 1984). Consistent with this is the observation that sprinters (100, 200m swimmers), as compared with endurance performers (400, 1500m swimmers), produce high lactate levels at speeds where the heart rate is low relative to its maximum (Treffene, 1979), indicative of a lower anaerobic threshold. Mader et al. (1978), using T_{LAC} , was successfully able to prescribe optimal training pace for developing the speed of a group of East German swimmers.

2.3.3b Cycling

While anaerobic threshold is often measured in cycling ergometry tests, only recently has it been related to actual cycling performances. In the study of Aunola et al. (1990) it was found that endurance time demonstrated a relationship to oxygen consumption at the anaerobic threshold ($r=0.66$). Loat and Rhodes (1991), using T_{VENT} as determined by excess CO_2 , predicted a level of work that could be performed for one hour without a significant elevation in blood lactate. The strongest support for anaerobic threshold in cycling are the studies of Coyle et al. (1991, 1988). Coyle et al. (1988) states that it is more accurate to express an individual's metabolic capacity for endurance exercise by reporting $\dot{V}O_2$ at T_{LAC} than it is to report $\dot{V}O_{2MAX}$. Further, Coyle et al. (1988) found "time to fatigue" to strongly relate to T_{LAC} ($r=0.90$). Coyle et al. (1988) also demonstrates the sensitivity of T_{LAC} with respect to "time to fatigue". When subjects performed at 88% of $\dot{V}O_{2MAX}$, one group was only 8% above T_{LAC} while the other was 34% above. The average times to fatigue were 60.8 and 29.1 minutes, respectively. Coyle et al. (1991) found the average work rate maintained during a one hour lab cycling performance best correlated to $\dot{V}O_2$ at T_{LAC} ($r=0.93$). They then compared this sustainable T_{LAC} determined work rate to a 40 km time trial performance with a strong relationship being evident ($r=0.88$). The oxygen consumption at T_{LAC} also seemed to be a sensitive indicator of cycling proficiency, as the better endurance cyclists clearly demonstrated higher thresholds.

2.3.3c Running

It would be impossible to mention all the anaerobic threshold studies that have produced strong relationships to run performance. Exercise intensities

selected quite voluntarily appear to be near the point where other investigators have shown that lactic acid production begins to increase (Karlsson, 1970; Knuttgen and Saltin, 1972). Coen et al. (1991) states that it is possible to provide training recommendations on the basis of anaerobic threshold, especially for endurance training. Variables such as T_{LAC} account for a greater proportion of the variance in running performance than running economy or $\dot{V}O_{2MAX}$ (Farrell et al., 1979; Tanaka et al., 1986; Yoshida et al., 1987). T_{VENT} during incremental exercise seems to provide an indication of lactate maximal steady-state while $T_{VENT} + 4.9\%$ showed a marked increase in blood lactate between 15 and 30 minutes (Yamamoto et al., 1991). Farrell et al. (1979) observed runners to set a race pace which closely approximates the run velocity at which lactate begins to accumulate in the plasma. Studies (Farrell et al., 1979; LaFontaine et al., 1981) have used anaerobic threshold predictions for distances from 3.2km to 42.2km with correlations between $r=0.91$ and $r=0.98$. Another study, supporting a performance relationship, was reported by Rhodes and McKenzie (1984) where T_{VENT} determined velocity was used to predict ($r=0.94$) actual marathon performance time. They suggested that run velocity at T_{VENT} may be critical in determining efficient running speed during marathons.

2.3.3d Triathlon

Anaerobic threshold determinations have produced similarly conflicting triathlon results. T_{VENT} demonstrated a weak relationship ($r=0.58$) while T_{LAC} demonstrated no relationship ($r=-0.37$) with performance times in the cycling portion of the Ironman triathlon (Roalstad, 1989). Van Rensburg et al. (1984) found an $r=-0.54$ between $\dot{V}O_2$ at the lactate turning point and cycle time. Despite these low correlations for anaerobic threshold Albrecht et al. (1986) was

able to set work loads based on T_{VENT} that produced stable heart rate and $\dot{V}O_2$ from 60 minutes of cycling to the end of 45 minutes of running.

2.3.3e Concerns

Despite the wealth of strong relationships to performances, and the abundance of research, anaerobic threshold remains a debatable and controversial area of research. Arguments question the existence of a threshold (Hughson et al., 1987) and methods of detection based on invasive or noninvasive determination (Davis et al., 1976). The initial definition of anaerobic threshold is constantly examined with respect to whether or not hypoxic conditions are present when lactic acid is being produced in the working tissues (Brooks, 1985). Powers et al. (1984), using gas exchange indices, were not able to reproduce the high correlations found earlier and concluded that T_{LAC} could not be accurately determined by these measures. As well, one of the most often used variables for estimating the point of T_{LAC} is based on a fixed (4 mmole) lactate concentration in the blood and has been criticized for over and under-estimating the true threshold (Stegmann and Kindermann, 1982; McLellan and Jacobs, 1989).

2.4 Conclusions

While the literature provides several lines of evidence to support a prediction concept in single sports there is a lack of research in multisport performances. Even the research that has been done seems to be very conflicting and demonstrates the wide range of variability within triathlon populations. The key determinants of success have all produced strong results in characterizing single sport performance ability although not without some conflicts representing methodological and mechanism concerns. The emergence

of other pace determining features with the passage of time and the effect of one sport on another make determination of triathlon success difficult. Despite this difficulty, there is a fundamental necessity for the successful triathlete to be one with the ability to have a highly developed oxygen transport and utilization system as well as the ability to efficiently produce a high energy output for prolonged periods without creating metabolic acidosis (O'Toole et al., 1989). This statement is indicative of an area of study that must have a basis in $\dot{V}O_{2MAX}$, economy of motion, and anaerobic threshold measurements that represent performance success. It is likely a lack of research and inappropriate research that has failed to produce better results in a triathlon setting.

CHAPTER 3

3.0 Methods and Procedures

3.1 Subjects

Eleven male subjects were selected from various running and triathlon clubs in the Vancouver area. Subjects were tested in the month prior to their participation in the 1991 Canadian Ironman Triathlon; all were in a highly trained state. The subjects were asked to refrain from heavy exercise 24 hrs prior to testing and to be 3 hrs postabsorptive.

3.2 Testing Procedures

All testing was performed at the University of British Columbia with the cycling and running sessions in the J.M. Buchanan Exercise Science Lab and the swimming sessions in the Aquatic Centre. During the first session, after the appropriate consent forms were signed, baseline measures of height, weight and body composition (hydrostatic weighing) were determined. The formula for hydrostatic weighing was as follows:

$$\text{body density} = \frac{W}{\frac{(W - UWW)}{C} - RV}$$

where W = weight on land (kg)
 UWW = under water weighing (kg)
 RV = residual volume
 C = temperature correction

Body density was then converted to percent body fat using the Siri equation

(%fat = $((4.95/\text{density}) - 4.5) * 100$). In addition, the first of three maximal oxygen consumption tests ($\dot{V}O_{2\text{MAX}}$) was performed either swimming, cycling or running. The remaining lab sessions consisted of the administration of the other two $\dot{V}O_{2\text{MAX}}$ tests not administered on the first day. A minimum of 48 hrs separated the testing sessions to try and prevent any carry-over from the previous test. After the lab sessions were completed the last phase of testing consisted of time measurements at the actual triathlon in Penticton, B.C. All the timing was done electronically by Racemate, the official timers for the Ironman Canada Triathlon. This timing resulted in both transition times being included in the cycling component time. To eliminate this from the cycling time each subject was instructed to start their bike cyclometer (timer) as they left the transition area at the start of the bike segment and stop it when they re-entered the transition at the end of the bike segment. The difference between official time and the cyclometer time was a measure of the transition time and could then be eliminated from calculations.

3.3 Testing Protocols

During all lab testing sessions heart rate was monitored with a Sporttester PE3000 heart rate meter. Expired gases were collected and analyzed using a Beckman Metabolic Measurement Cart interfaced with a Hewlett Packard Data Acquisition System. All maximal oxygen consumption tests for determination of T_{VENT} were preceded with a warm-up and terminated upon volitional fatigue. The warm-up consisted of an explanation of the testing procedures followed by a physiological warm-up with all the equipment in place against a light resistance load. This provided the subjects with an opportunity to become familiar with the equipment and the actual process for gathering data during the test. Volitional

fatigue was defined by the criteria for the particular test or by the reaching of $\dot{V}O_{2\text{MAX}}$ as defined by the following criteria:

- 1) The oxygen consumption ceases to increase linearly with rising workload and approaches a plateau or drops slightly, the last two values agreeing within $\pm 2 \text{ ml}\cdot\text{kg}\cdot\text{min}^{-1}$.
- 2) Heart rate should be close to the age predicted maximum.
- 3) Respiratory exchange ratio is greater than 1.10.

The three sport protocols were as follows:

1) Swimming -

All swimming sessions were confined to a roped-off section of the indoor pool to minimize interference from other swimmers and any wave action they may cause. The water temperature in the pool at this time of year (July, August) tends to vary between 26 and 29 °C. The subjects were instructed to wear their wetsuits (they would be worn in the race) and a rope tether was attached via two belt loops on either side of a waist harness. The rope pulled at a slight angle from the bottom pulley of the frame to the waist harness. The protocol started at an initial load of 3.5 kg with 250 g increases each minute while the subject was required to maintain swimming over a marked section on the bottom of the pool. The additional measure of stroke rate was determined for each minute of the test by counting the number of strokes over a 30 second interval. This procedure was done from 15 seconds to 45 seconds of each minute to minimize the effect of workload changes on the stroke rate determination. Volitional fatigue was defined by either the subject's inability to maintain swimming over the marked position in the pool against the load or their own termination. Subjects were

given a warning when they started to drop back to reassume the position over the marker, if they were unable the test was terminated.

2) Cycling -

A mechanically braked Monarch bicycle ergometer was used with the protocol starting at an initial workload of 88.2W and having progressive increases of 22.1W each minute. Volitional fatigue was defined by either the inability to maintain the required test cadence of 90rpm or the subject's own termination of the test. The cadence was clearly visible to the athlete at all times on the Monarch's readout screen. If the subject cycled above or below the test cadence he was instructed to resume 90 rpm and maintain it for the duration of the test.

3) Running -

Procedure involved a continuous (zero grade) treadmill run protocol started at an initial velocity of 5 mph and increased 0.5 mph each minute. Volitional fatigue was defined by the athlete no longer being able to maintain the treadmill velocity.

Ventilatory thresholds were determined on the basis of a disproportionate (nonlinear) increase in the excess CO_2 (EXCO_2) elimination curve over time. This determination was made by visual inspection of three observers not directly involved in the study, who had experience in measuring threshold. All three were volunteers with considerable background in testing endurance athletes and using excess CO_2 for determining T_{VENT} in a research setting. Observations were made separately and an agreement was reached on the location of the

threshold. In the event of a disagreement the $\dot{V}_E/\dot{V}O_2$ curve was used to clarify the actual threshold point.

The velocity that T_{VENT} corresponded to was made for each component sport as follows:

1) Swimming -

The stroke rate (strokes·minute⁻¹) measured at T_{VENT} was converted to velocity by using a pool swim to measure the stroke length (metres·stroke⁻¹). While swimming at the desired stroke rate the stroke length was measured over a marked (middle 15 m) section of the 25 m pool. This minimized the effect of the turn and the subjects were directed not to push-off hard from the ends of the pool. These two values were then multiplied together to give the velocity (see Appendix A for a sample calculation).

2) Cycling -

T_{VENT} was converted to velocity using a developed regression equation relating workload at T_{VENT} to velocity during a 40 km cycling performance (see Appendix B for a precise explanation).

3) Running -

Simply the measured velocity of the treadmill at the determined threshold point (see Appendix C for sample calculation).

Each velocity was then converted to an estimated performance time based on the distance of that component of the triathlon.

3.4 Experimental Design and Data Analysis

An analysis of variance was used to compare the dependent variables $\dot{V}O_{2\text{MAX}}$, T_{VENT} absolute, T_{VENT} relative, and heart rate at T_{VENT} (absolute and relative) for each component sport. A statistical significance level of 0.01 was used in the analyses. Simple linear regression correlation coefficients were calculated to compare estimated and actual performance times (minus the transition times) for each component sport. A multiple linear regression was then performed to predict overall triathlon time from the estimated component sport times.

CHAPTER 4

4.0 Results and Discussion

4.1 Results

Eleven trained triathletes participated in this study prior to competition in the 1991 Ironman Canada Triathlon. Note that one subject dropped out during the cycling portion of the triathlon, consequently his data were not used in the study. Descriptive data (age, height, weight, and body fat) for the 10 subjects are presented in Table 1. Triathlon experience and training mileage is summarized in Table 2.

Table 1: Descriptive data for all subjects.

	AGE (years)	HEIGHT (cm)	WEIGHT (kg)	BODY FAT (%)
\bar{X}	29.7	179.8	76.8	11.4
SD	± 3.1	± 5.6	± 7.9	± 2.2

Table 2: Weekly training mileage and previous triathlon experience for all participants.

		WEEKLY MILEAGE (km)		
		SWIMMING	CYCLING	RUNNING
	NUMBER OF PREVIOUS TRIATHLONS			
\bar{X}	16	10	296	48
SD	± 12	± 3.5	± 73	± 8

The variables of heart rate and $\dot{V}O_2$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) were measured as an absolute value at T_{VENT} and as a relative percentage of maximum ($T_{\text{VENT}}/\text{MAX}$) for the three events of swimming, cycling, and running (Table 3). An ANOVA comparing swimming, cycling, and running revealed significant differences ($p < 0.01$) between cell means for the absolute and relative scores on heart rate and $\dot{V}O_2$. Tukey's HSD *post hoc* analysis demonstrated that the significant difference in heart rate at T_{VENT} (HSD = 17.27, $p = 0.01$) was between swimming and running (difference between pair of means (diff) = 20.5) and cycling and running (diff = 17.5) while differences between cycling and

swimming were nonsignificant (diff = 3). This pattern was also observed in the relative heart rate (HSD = 4.75, $p = 0.01$) where significant results were swimming and running (diff = 5.2) and cycling and running (diff = 6.6) with nonsignificance between cycling and swimming (diff = 0.6). Similarly, $\dot{V}O_2$ at T_{VENT} (HSD = 8.35, $p = 0.01$) revealed significant results for swimming and running (diff = 16.6) and cycling and running (diff = 11.6) with a nonsignificant result between cycling and swimming (diff = 5). The final variable showing this pattern was the relative T_{VENT} (HSD = 7.56, $p = 0.01$) where swimming and running (diff = 8.9) and cycling and running (diff = 14) were significant while cycling and swimming (diff = 5.1) was nonsignificant. Investigation of the variable $\dot{V}O_{2MAX}$ (HSD = 8.83, $p = 0.01$) revealed swimming and running significant (diff = 14.7), swimming and cycling significant (diff = 10.7) and cycling and running nonsignificant (diff = 4).

Table 3: Heart rate and $\dot{V}O_2$ measured at T_{VENT} and expressed as a percentage of their maximal value.

	SWIMMING		CYCLING		RUNNING		
	\bar{X}	SD	\bar{X}	SD	\bar{X}	SD	
HEART RATE AT T_{VENT} (bpm)	147.6	± 13.2	150.6	± 13.5	168.1	± 10.3	* **
HEART RATE RELATIVE (%)	86.9	± 3.5	85.5	± 3.9	92.1	± 2.7	* **
$\dot{V}O_2$ AT T_{VENT} ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	36.2	± 5.2	41.2	± 6.7	52.8	± 5.9	* **
$\dot{V}O_2$ RELATIVE (%)	74.5	± 5.9	69.4	± 5.3	83.4	± 4.9	* **
$\dot{V}O_{2\text{MAX}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	48.6	± 5.8	59.3	± 7.5	63.3	± 5.5	* ***

* = significant difference ($p < 0.01$) between swimming and running

** = significant difference ($p < 0.01$) between cycling and running

*** = significant difference ($p < 0.01$) between cycling and swimming

Estimated times and race paces for each component event of the triathlon were determined utilizing physiological testing related to that sport. The variables stroke rate, in strokes·min⁻¹ (\bar{X} = 32.5, SD = ± 2.5), and stroke length, in metres·stroke⁻¹ (\bar{X} = 1.88, SD = ± 0.20), measured during the swim testing sessions were used to estimate time (min) and pace (min·mile⁻¹) for this component of the triathlon. The resulting estimated and actual times (min) and paces (min·mile⁻¹) for swim testing are shown in Table 4 (for more detail regarding the actual determination of the swim estimation refer to Appendix A).

Since mph could not be determined directly from testing for the cycling component, a linear regression was developed using excess CO₂ at T_{VENT} (Table 5). This equation related mph and this variable measured during the cycling component of the 1991 English Bay triathlon. Since the resulting prediction equation ($r = 0.68$) was based on a short course triathlon (40 km) cycling component it was necessary to extrapolate this to mph in Ironman distance (112 mile) cycling. This was accomplished using 26 subjects who participated in both the Ironman and the English Bay triathlon. The mph in both cycling performances were correlated ($r = 0.91$) to estimate the necessary distance correction factor (Table 5).

Table 4: Estimated and actual swimming times and paces for the Ironman Triathlon.

	ESTIMATED		ACTUAL	
	TIME (min)	PACE (min·mile ⁻¹)	TIME (min)	PACE (min·mile ⁻¹)
\bar{X}	64.2	26.7	67.1	27.97
SD	±5.6	±2.3	±7.8	±3.2

Table 5: Equations used in the determination of the cycling portion of the Ironman Triathlon.

	EQUATION	r
PREDICTED MPH (based on 40 km performance)	$\text{MPH} = (\text{EX}_{\text{CO}_2} * 0.845) + 12.07$	0.68
CONVERSION FACTOR (40 km to 112 mile)	$\text{MPH (112 mile)} = (40 \text{ km MPH} * 0.9988) - 3.35$	0.91

These equations resulted in the estimated time (min) and pace (mph) shown with the actual race values in Table 6. A more detailed explanation of this calculation for the cycling component is presented in Appendix B.

Table 6: Estimated and actual cycling times and paces for the Ironman Triathlon.

	ESTIMATED		ACTUAL	
	TIME (min)	PACE (mph)	TIME (min)	PACE (mph)
\bar{X}	380.0 (6:20)	17.9	344.4 (5:44)	19.5
SD	±45.2	±2.1	±13.0	±0.75

The run component of the triathlon utilized the velocity at T_{VENT} on the treadmill to produce the estimated time (min) and pace (mph) shown with the actual time and pace for the triathlon in Table 7. An explanation of the development of the run estimation is presented in Appendix C.

Table 7: Estimated and actual run times and paces for the Ironman Triathlon.

	ESTIMATED		ACTUAL	
	TIME (min)	PACE (mph)	TIME (min)	PACE (mph)
\bar{X}	174.5 (2:55)	9.1	258.6 (4:19)	6.4
SD	±15.7	±0.9	±64.4	±1.4

From these results linear regression equations were developed to estimate actual time for each respective component of the triathlon, and to use that to develop the overall predictor equation (Table 8).

Table 8: Conversion factors from estimated to actual for each component and overall time in the Ironman Triathlon.

	EQUATION	r
SWIMMING	$\text{ACTUAL SWIM} = 1.15 * \text{ESTIMATED SWIM} - 6.75$	0.83
CYCLING	$\text{ACTUAL CYCLE} = 0.22 * \text{ESTIMATED CYCLE} + 262.6$	0.70
RUNNING	$\text{ACTUAL RUN} = 3.03 * \text{ESTIMATED RUN} - 267.1$	0.76
OVERALL	$\text{ACTUAL OVERALL} = (-3.58 * \text{EST. SWIM}) + (-0.10 * \text{EST. CYCLE}) + (3.76 * \text{EST. RUN}) + 291.35$	0.89

4.2 Discussion

Despite the controversy and debate with respect to nomenclature, mechanisms, detection, and interpretation (Brooks, 1985; Davis, 1985), there is little dispute over the strong relationships that have been demonstrated between anaerobic threshold and performance. While much of this research has focused on running studies (Farrell et al., 1979; Morgan et al., 1989; Maughan and Leiper, 1983), other investigations involving cycling, swimming, cross-country skiing, etc. have produced similarly strong results (Mader et al., 1978; Coyle et al., 1991). Most of this performance research has been confined to single sport endurance events. Now, with the emergence of multiple sport endurance contests (triathlon, duathlon), the ability of ventilatory threshold (T_{VENT}) to characterize performance in this new setting is questionable. Not only must measurements characterize the component sports but they must also take into account the prior exercises which increase the physiological demands of performing subsequent events (Kreider et al., 1988). The purpose of this study was to investigate if T_{VENT} measured in swimming, cycling and running was capable of predicting triathlon performance (time) success.

The subject pool used in this study appears to be typical of other studies in terms of the descriptive characteristics of the triathletes (Burke and Read, 1987; Roalstad et al., 1987; Ireland and Micheli, 1987). The triathletes tend to be older than comparable single sport endurance performers (Kreider et al., 1988; Kohrt et al., 1987a; O'Toole et al., 1987). This is probably a factor of the "newness" of the sport and as it grows the population of triathletes will be younger. As well, most athletes come to triathloning after competing in one of the single sports, so it would be expected that they are older. In terms of the other descriptive characteristics of height, weight, and body fat, they are

undistinguished from other single sport athletes (O'Toole et al., 1987; Roalstad, 1989).

The weekly mileage for these subjects is similar to other triathletes with respect to swimming (typical = 10.5 km) and cycling (typical = 300 km) while the running is low (typical = 72 km) (O'Toole et al., 1989). This low weekly run mileage will be discussed in the context of how it may relate to the results found in this study. As with other studies, there is a wide interindividual variability with respect to training mileage in the three component sports (O'Toole, 1989).

The values for heart rate and oxygen consumption are consistent with respect to other research (Dengel et al., 1989). The hierarchy of $\dot{V}O_{2MAX}$ values is typical (run>cycle>swim) but the absolute scores are less than comparable single sport athletes (Astrand and Rodahl, 1977). This may be reflective of the reduced training volume in any one area and/or specific adaptations that triathletes undergo in training related to their sport (Kohrt et al., 1987b). The absolute scores demonstrate the expected pattern between running and swimming, and running and cycling with the exception of run-cycle $\dot{V}O_{2MAX}$. While the differences between run-cycle were nonsignificant on this variable the drop from running to cycling is consistent with previous triathlon research. The difference of 6.7% compares well to the work of Kohrt et al. (1987a) and O'Toole et al. (1987) where the maximums are 3 to 6% less in cycling. This drop of 3 to 6% for $\dot{V}O_{2MAX}$ from running to cycling is somewhat less than highly trained runners would show (9 to 11%) (Roalstad, 1989). The hierarchy tends to demonstrate the highest $\dot{V}O_{2MAX}$ values for treadmill running, with cycling approximately 90% (Faulkner et al., 1971; Miyamura et al., 1978) and swimming approximately 80% (Holmer et al., 1974; Magel et al., 1975) of the running value. This relationship is altered in athletes who are trained cyclists or

swimmers. Highly trained cyclists may equal or exceed their treadmill running $\dot{V}O_{2MAX}$ on cycle ergometry testing (Kohrt et al., 1989) likely by virtue of a more sport specific testing procedure. Several studies (Roalstad, 1989; Hagberg et al., 1978; Withers et al., 1981) state that triathletes most resemble cyclists. While the triathletes generally do not equal or exceed their treadmill run $\dot{V}O_{2MAX}$, like elite cyclists there is a training specificity, resulting in less of a gap between the run and cycle $\dot{V}O_{2MAX}$. This relationship is not unique to this study (O'Toole et al., 1987; Kohrt et al., 1987b) and may reflect a specific adaptation to triathlon type training versus single sport training.

For the variable $\dot{V}O_{2MAX}$ only swimming and cycling illustrated the hypothesized result, with the cycling $\dot{V}O_{2MAX}$ significantly greater than the swimming $\dot{V}O_{2MAX}$. This study demonstrated a swim $\dot{V}O_{2MAX}$ value at 77% of the running $\dot{V}O_{2MAX}$ which is typical of trained runners tested in both modes. Since highly trained swimmers may reduce the difference between swimming and running, it was thought triathletes might demonstrate this result, although to a lesser degree. Studies by Dengel et al. (1986) and Kohrt et al. (1987b) found a reduction in the difference, while Kohrt et al. (1989) did not. Thus, the literature tends to be equivocal on this point. The similar finding to Kohrt et al. (1989) may indicate that the relatively low weekly volume of training (elite swimmers' daily training distance is about equal to triathletes' weekly swim training distance) was insufficient to develop training specificity as seen in cycling. The variables HR and $\dot{V}O_2$ at T_{VENT} were similar ($p > 0.05$) for swimming and cycling. This might be accounted for by a slightly low estimated threshold in cycling (Kohrt et al., 1989). The mean $\dot{V}O_{2MAX}$ value is typical of other studies which have ranged from 54.4 ml·kg⁻¹·min⁻¹ (Kohrt et al., 1987b) to 66.7 ml·kg⁻¹·min⁻¹ (O'Toole et al., 1987) for men on cycle ergometry testing. The low threshold value might be

accounted for by the type of training most subjects performed. Most participants followed a high volume (about 296 km·week⁻¹) format with very little "quality" training. To improve T_{VENT} most studies indicate a high intensity (near or slightly above threshold) type protocol (Pate and Branch, 1992). O'Toole (1989) documented a low amount of interval training (20%) on the bike by a large survey of triathletes. Thus, since most subjects have trained based on volume for cycling as opposed to higher intensity, the ability of T_{VENT} to separate differences in levels of performance is lessened. Subjects are working at a lower percentage of maximum in cycling than the other two component sports as demonstrated in these results.

On the relative measures of HR and $\dot{V}O_2$ it was hypothesized that there would be nonsignificant differences between swimming, cycling and running. This was only true for swimming and cycling with running being significantly greater than either of the other component sports. The high percentage may reflect the previous training of these athletes. Approximately 75% of triathletes have a running background (Ireland and Micheli, 1987) and the higher T_{VENT} may reflect a relationship between experience and performance. Certainly, studies have shown years of experience to be highly correlated with performance (Magel et al., 1975; O'Toole, 1989). Kohrt et al. (1989) suggest that this lower percentage found in cycling may indicate that triathletes have a greater potential to improve in cycling than in running. This lower T_{VENT} in cycling may reflect the need to devote a greater proportion of training or at least an increase in the intensity of the training in order to achieve the similar training status as found in running. In this study, the one subject from a cycling background had the highest cycling T_{VENT} estimated percentage. This may also simply reflect large interindividual variability, coupled with the small sample size

of the present study. This condition may result in extreme scores influencing results more than if a large sample study were employed.

The results of swim testing produced an estimate 2.9 minutes faster than actual swim time for that component of the Ironman triathlon. This result ($r=0.83$) indicates that 69% of the actual time variability was accounted for by the estimated time value. This result seems consistent with the T_{VENT} concept. T_{VENT} assumes participants will set a maximum pace that could be sustained indefinitely, without inducing metabolic acidosis (Coyle et al., 1988; Williams and Cavanagh, 1987; Kumagai, 1982). Since this is the first event, sport intrinsic fatiguing factors (fluid, fuel, etc.) are not likely to severely limit pace (O'Toole et al., 1989). As well, the low number of confounding factors would suggest that the correlation between actual and estimated swim performance should be the highest of the three component sports, and indeed this was the case. Thus, this physiological variable, explaining 69% of the variability, stresses the importance of other factors, particularly mechanical efficiency which may also affect performance (Kohrt et al., 1989). The study of Toussaint (1990), comparing elite swimmers to triathletes, found that they both had similar ability to do work but the differences in technique separated the triathletes from the more skilled swimmers. The inefficient swimmer may expend more than twice the calories during submaximal swimming compared to the efficient swimmer. This would lead to a generalized and localized fatigue (Holly et al., 1986). This is paramount in a triathlon when considering the majority of the competitive distance is still to come and it is necessary to conserve energy. From the perspective of competitive experience, the subjects were well prepared (average of 16 triathlons completed) and less likely to push pace this early in the event. Only two subjects were faster (both 4 minutes) than their estimated time, one being the strongest swimmer in the study.

Cycling results were much more confusing, with the estimated time being 36 minutes slower than actual time. The correlation between estimated and actual time resulted in 49% ($r=0.70$) of the variance being explained by the estimator. It was expected that all estimated results would be faster than actual times. Given the increasing influences of intrinsic factors (fuel, fluid, thermoregulatory mechanisms, etc.) and extrinsic factors (heat, humidity, terrain, etc.) which would reduce the ability to maintain speed and the inability of T_{VENT} to account for these, it seemed a reasonable assumption. There are several possible explanations for this observation. Firstly, it may reflect an inadequacy in the chosen methodology. The inability to measure speed directly in the testing environment necessitated the indirect determination using a short course triathlon performance. Since many of the factors that adversely effect performance will also be present in a short course triathlon (however to a lesser degree) the cycling equation developed will in some way account for this variability and reduce the ideal speed determined by a solely lab developed estimation. As well, the extrinsic factors of terrain, weather, etc. will also be present, confounding the determination of cycling pace. Another possible explanation is that the methodology employed underestimates the true threshold. The few studies that have looked at triathletes T_{VENT} relative to performance have been unsuccessful with correlations between T_{VENT} and bike finish times in an Ironman triathlon ($r = -0.26$)(O'Toole et al., 1989). While some of the reduced relationship from swim to cycle is methodological, considerable variability is due to factors not present while swimming (terrain, heat, etc.). Also the cumulative effect of time magnifies the factors that were evident in the swim. Certainly, one of the conclusions of the low correlation studies has been that the upper limit of pace for cycling is being set by other factors as opposed to physiological considerations represented by T_{VENT} (O'Toole et al., 1989). The

emergence of other factors was evident in the bike portion of the triathlon, as one subject dropped out due to dehydration. By this time in the triathlon, the cumulative effects of time, distance, and heat are beginning to take their toll in terms of dehydration, electrolytic abnormalities, and exhaustion (Laird, 1989). Although the swim is a relatively small component of the total event, it may have pronounced effects on subsequent performance. Kreider et al. (1988) found that prior swimming would increase core temperature at the onset of cycling. Thusly, thermoregulatory and cardiovascular adjustments occur sooner than they would with no prior swimming. In this study the lower correlation may also be reflective of a very homogeneous sample (344.4 ± 13 minutes), with respect to actual cycling time. In addition, the idea of maintenance of efficiency as the ultimate determinant of triathlon success (Kreider et al., 1988) may be less physiological (T_{VENT}) and more biomechanical (technique), accounting for a considerable portion of the variability.

The run results produced the greatest disparity between estimated and actual times with an average of one hour and 24 minutes difference. As would be expected the estimated time was faster than the actual time. There was considerable variability (258.6 ± 64.4 minutes) in run performances with the estimated time able to explain 58% of the variability in actual time. The effects of prior activity in swimming and cycling (subjects have been active between about 6 and 7 hours) are likely to be even more pronounced. The large difference between estimated and actual times provides support for other factors setting pace limits. While these intrinsic and extrinsic factors are present, another observation may explain some of the decrease in run race pace. The difference in combined swim and cycle time from fastest to slowest subject is one hour and one minute while the combined swim, cycle, and run difference from fastest to slowest is 3 hours and 48 minutes. This is a considerable amount

of variability to be added during the run segment. This difference is largely accounted for by the inability of slower subjects to maintain pace. The well-trained runners are better able to maintain race paces that approximate their training pace, while the less well-trained athletes demonstrate an inability to maintain training pace (O'Toole, 1989). This may be the result of these subjects having difficulty maintaining a constant T_{VENT} estimated pace for some portion of the triathlon prior to running. The variable terrain found at the Ironman Canada Triathlon would also be an interfering factor. The considerable elevation changes during the bike portion produce extreme speed variability making it difficult to maintain a steady work output. Roalstad et al. (1987) found triathletes with the least fluctuations in heart rates tended to have better finishing times than those with wide variability. The terrain creates a condition that must ultimately place some constraints on the ability of T_{VENT} to estimate during the bike portion of the triathlon. This result is certainly consistent with the concept of T_{VENT} and the expected result if a subject were to perform for any length of time above the defined limit of aerobic ability (Farrell et al., 1979). The homogeneous cycling performances may also support this result, if the slower cyclists' actual performances were faster than expected. The greatest difference between actual and estimated time was in fact between the slowest cyclists with all performances much faster than estimated (by an average of 74 minutes). Therefore, there is some evidence for cycling above T_{VENT} with a subsequent adverse effect on running. This would explain some of the wide variability seen in the slower subjects. Another factor that may account for variability in running is the low mileage done for this component in training. O'Toole (1989) found that of the subjects who did not finish the two main reasons were; (1). inappropriate race strategy and (2). too little training (particularly long distance bike rides or long runs). Some coaches suggest that training in swimming and cycling

provides a "crosstraining" benefit that would offset the low mileage training in running. Previous research suggests that this is not true. Swim training (Gergley et al., 1984; Magel et al., 1975) and cycle training (Town and Sinning, 1982; Pechar et al., 1974) have both failed to demonstrate improvement in run training. Thus, a lack of sufficient run mileage may also represent some of the variability.

When all three component sports are taken into account in a multiple linear regression a strong correlation to the actual overall time ($r=0.89$) resulted. Thus, the combined variability represented by each of the component sports is able to predict overall time better, accounting for 78% of variability, than its individual component sport. This also suggests that each sport's variability represents an important part of the variability seen in a combined sport like triathlon.

These results support the importance of an understanding of these other factors influencing performance. Successful triathlon performance appears to be impacted upon by the ability to maintain thermal and mechanical efficiency throughout the event (Kreider et al., 1988). Most of the metabolic abnormalities that develop are time dependent and cumulative as the triathlon progresses. An example of this time effect is found in the research of Laird (1989) where in going from a short course triathlon to Ironman distance, the average percent dehydration increased from 1.7 to 3.7%. Certainly, absolute fluid loss increases over longer distances. While the most marked differences are seen in the run, they are more the effect of the total duration as opposed to the marathon itself (Farber et al., 1991). Relationships reflect this emergence of pace determining factors if we consider that in the study of Rhodes and McKenzie (1984) an $r=0.94$ was found between estimated and actual time. While this study, using the exact same equipment and methodology found $r=0.76$ for the marathon run component of the triathlon. In comparison to other endurance activities

indications of dehydration were much greater in Ironman triathletes (van Rensburg et al., 1986). The most common reason for requiring medical attention at the Hawaii Ironman is dehydration (Hiller et al., 1987; Laird, 1987). Sawka et al. (1985) recognized that dehydration accompanied with thermal stress may significantly decrease work output. In terms of electrolytes, incidence of hyponatraemia are directly related to race distance (O'Toole et al., 1989). Salt-depletion heat exhaustion is characterized by fatigue, nausea, muscle cramps, etc. (Laird, 1989) This combined with dehydration and increased sweat rate will have profound results on fatigue. Certainly, nutritional replacement has been well documented with respect to its role in endurance performance (Costill, 1988). Emerging research suggests there are likely extra considerations that need to be made in events of the duration of ultraendurance triathlons. Typical carbohydrate replacement protocol, like that done in marathoning, may not be a sufficient rate of replacement for these increased duration events (Applegate, 1989). As well, the use of solid food is well accepted in ultraendurance triathlons (Applegate, 1989). Further research is needed with respect to the appropriate protocols for nutritional replacement during Ironman distance triathlons to minimize the adverse effects of running out of energy.

Despite the other factors interfering with the actual estimation of performance, the underlying mechanisms support the concept of T_{VENT} . Ultimately, the triathlon is a contest requiring a series of endurance events to be done sequentially at optimal pace without creating fatigue that will hinder performance in the next event (O'Toole et al., 1989). T_{VENT} is designed to identify the point where work may be performed for indefinite durations as energy requirements are being supplied predominantly through unlimited aerobic energy sources, while waste products are being adequately removed (Anderson and Rhodes, 1989). While there are many different methods for determining

T_{VENT} , excess carbon dioxide (CO_2) combines a strong mechanism base with a strong relationship to performance research. Carbon dioxide production will increase with exercise due to the metabolism of fats and carbohydrates until the T_{VENT} breakaway point at which time there will be a secondary (nonmetabolic) increase in CO_2 due to the buffering of lactic acid by bicarbonate (Anderson and Rhodes, 1989). This provides for a direct tie between the generation of excess CO_2 and the increased production of lactic acid which is strongly related to fatigue (Sjodin and Svedenhag, 1985). Studies suggest that 90-94% of the lactic acid produced is immediately buffered by the bicarbonate buffering system (Wasserman et al., 1986). Thus, excess CO_2 is representing the magnitude of lactic acid production through the glycolytic pathways and the organism's buffering capacity (Anderson and Rhodes, 1991) and will continue to increase as long as the rate of lactic acid production is increasing (Loat and Rhodes, 1991). While excess CO_2 changes do not represent the actual occurrence of blood lactate accumulation they do seem to track the changes taking place (Anderson and Rhodes, 1989). This "tracking effect" demonstrates the strong relationship ($r=0.92$) between excess CO_2 and blood lactate changes (Langill and Rhodes, 1992). It is suspected that this difference is due to the excess CO_2 being freely diffusable across the cell membrane while the lactate molecule experiences a "translocation hindrance" delaying increases in the blood (Stainsby, 1986). It is suggested that this hindrance represents a delayed lactate transport caused by low muscle membrane lactate permeability and a change in capacitive effects in muscle concentration of lactic acid (Stainsby, 1986). This resulting delay in blood lactate accumulation may in fact suggest that excess CO_2 more directly approximates changes in intramuscular lactate production and accumulation (Volkov et al., 1975; Issekutz and Rodahl, 1961). Combined with this support for excess CO_2 's ability to define a critical intensity of lactate accumulation, the

performance research supports similarly strong ties. Hearst and Rhodes (1982) found exercising at T_{VENT} to be an appropriate intensity to maintain a significantly low blood lactate concentration while exercising at an intensity $1 \text{ km}\cdot\text{hr}^{-1}$ above T_{VENT} elevated the lactate. The study of Loat and Rhodes (1991) found excess CO_2 defined a T_{VENT} that could be sustained for one hour of cycling without significant elevations in blood lactate.

Endurance, as it relates to competition, can be thought of as the capacity to achieve and maintain a high average speed over the distance of the race. It is with this in mind, that the concept of T_{VENT} has emerged to try to identify this point of maximum sustainable pace. While other factors such as substrate depletion, temperature regulation, fluid and electrolyte balance will contribute to fatigue and make it difficult to represent a sustainable work rate (Carnevale and Gaesser, 1991) there is still underlying physiological mechanisms that T_{VENT} appears to represent. Between 49 and 69% of the individual component sport variability and 78% of the total triathlon variability is accounted for by these measurements. Despite adverse conditions having reduced the ability of T_{VENT} to determine pace there still remains a connection between performance and threshold measurements that extends from single to multiple endurance sport contests. Triathlon is a comparatively new sport and considerably more research is needed into the determinants of success. Particular emphasis should focus on understanding the unique physiological adaptations that take place in triathletes relative to single sport athletes and examining the role the various factors play in decreasing performance. However, research should not dismiss the use of T_{VENT} in this sport setting.

CHAPTER 5

5.0 Summary and Conclusions

5.1 Summary

In theory, there is considerable evidence to suggest that it is possible to estimate athletic performance in endurance sports. These sports are contested by athletes who will, regardless of their competitive ability, try to sustain a race pace that maximizes their physiological capacities. The use of lab data to estimate such performance is an extremely attractive concept since it could offer a more scientific basis for training and selection of athletes.

Several physiological factors ($\dot{V}O_{2\text{MAX}}$, economy of motion, and anaerobic threshold) have been investigated with varying degrees of success. Among these, the anaerobic threshold seems to have the most potential for characterizing endurance sport performance. The term "anaerobic threshold" has undergone considerable change in the years since its initial development by Wasserman and McIlroy (1964). Its measurement based on the ventilatory measure excess CO_2 has produced strong relationships to endurance sport performance in running and cycling (Rhodes and McKenzie, 1984; Loat and Rhodes, 1991; Hearst and Rhodes, 1982). It has also been shown to have a strong relationship to the lactate threshold (Anderson and Rhodes, 1991; Langill and Rhodes, 1992) and possibly the intracellular production and accumulation of lactate (Issekutz and Rodahl, 1961).

Anaerobic thresholds have been used in sports like swimming, cycling, and particularly running to develop performance based relationships with some success. The comparatively new sport of triathloning has presented a new set of

questions with regard to estimating performance. Due to the multiple modes of competition within the same contest it is not known whether the same features governing single sports also apply to triathlon. Problems of performing sequential events and extreme duration pose restrictions that must be considered. It was the purpose of this investigation to determine if ventilatory threshold measurements in swimming, cycling, and running could be extended to triathlon in an effort to characterize performance.

This study found the estimated single component sport times to correlate to actual triathlon times in swimming, cycling, and running with $r=0.83$, 0.70 , 0.76 respectively. Overall triathlon performance found $r=0.89$ between the combined three sport estimated times and the actual total time. Linear regression equations were produced such that actual time could be calculated from estimated times (in minutes) with the following results:

$$\text{actual swim} = 1.15 * \text{estimated swim} - 6.75$$

$$\text{actual cycle} = 0.22 * \text{estimated cycle} + 262.6$$

$$\text{actual run} = 3.03 * \text{estimated run} - 267.1$$

$$\text{actual overall} = (-3.58 * \text{est. swim}) + (-0.10 * \text{est. cycle}) + (3.76 * \text{est. run}) + 291.35$$

These findings demonstrated an underlying physiological base for triathlon performance that was represented by ventilatory threshold. Unfortunately, other factors resulting from the cumulative effect of time, heat, and terrain diminish the ability to use ventilatory threshold as a predictor.

5.2 Conclusions

- 1) Ventilatory threshold accounted for 78% of the variability in pace in an ultraendurance sport setting.
- 2) This ability is compromised by other factors that confound the ability to estimate pace.

5.3 Recommendations

- 1) It would be beneficial to make some measurements of pace at the beginning, middle, and end of each component sport during the race to see how well subjects actually do maintain constant pace.
- 2) The development of a correction factor that could be carried-over from one component sport to the next to account for cumulative effects is needed.
- 3) A more direct methodology for estimating the cycling component time would likely improve this weakest of the correlations.
- 4) Instead of comparing the T_{VENT} determined speeds to an actual triathlon, compare then to a simulated laboratory triathlon to eliminate some of the extraneous variables.
- 5) At this stage most of the triathlon research is equivocal, so continued research in this area is necessary to gain a better idea of those factors contributing to triathlon success.
- 6) Still more research is needed into anaerobic threshold, particularly the underlying intracellular mechanisms.

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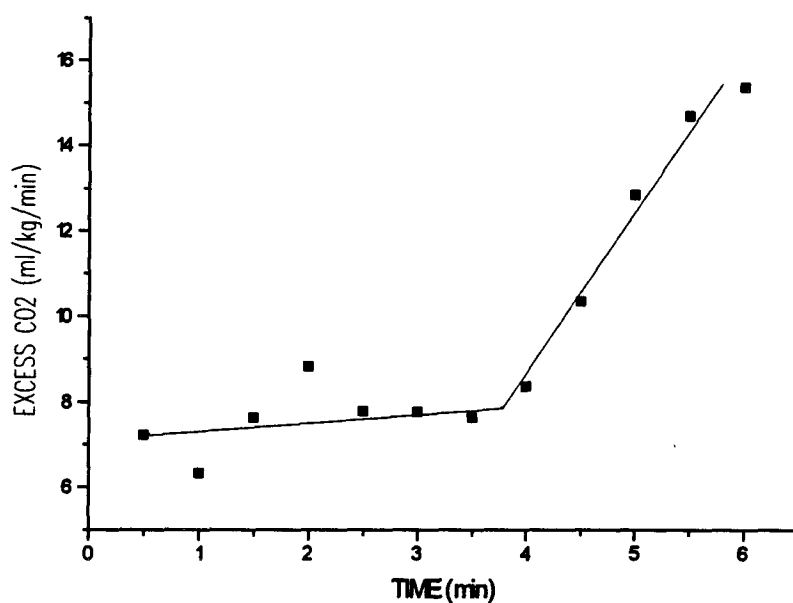
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APPENDIX A

Sample calculation for the estimation of time in the swimming component of the Ironman Triathlon.

- 1) The ventilatory threshold (T_{VENT}) point was determined by a graph of excess CO_2 vs. time during the tethered swim performance.



- 2) Since stroke rate was measured each minute, the T_{VENT} stroke rate was simply the value at its time of occurrence.

eg: $T_{VENT} = 4$ minutes stroke rate at $T_{VENT} = 30 \text{ strokes} \cdot \text{min}^{-1}$

- 3) To determine the stroke length that corresponded to this stroke rate several swim repeats were performed. The subject swam the measured stroke rate over a marked section of the pool while the number of strokes to cover the distance was counted.

eg: Swimming at T_{VENT} stroke rate = $30 \text{ strokes} \cdot \text{min}^{-1}$,
determined stroke length = $1.96 \text{ metres} \cdot \text{stroke}^{-1}$

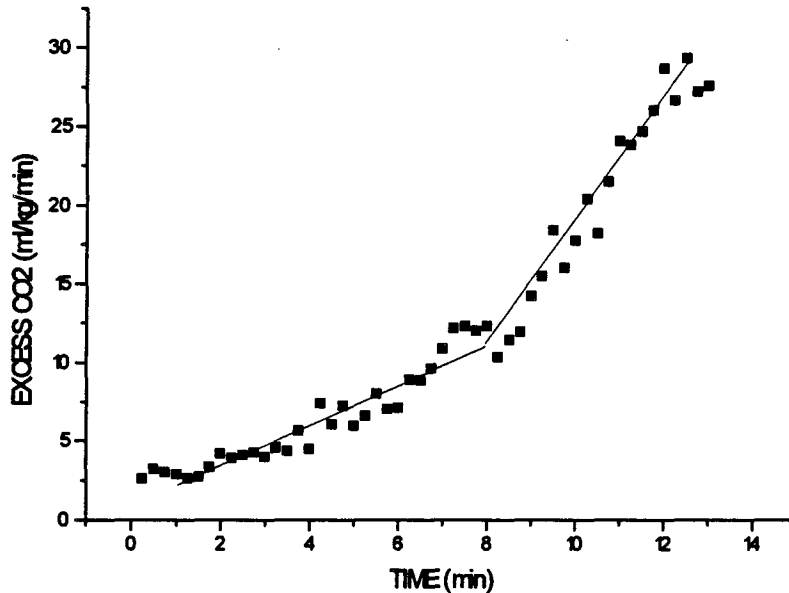
4) These 2 values were then multiplied together to give the velocity at T_{VENT}
eg: $30 \text{ strokes} \cdot \text{min}^{-1} * 1.96 \text{ metres} \cdot \text{stroke}^{-1} = 58.8 \text{ metres} \cdot \text{min}^{-1}$

5) This was then converted to minutes using the known distance of the swim
component (2.4 miles)

eg: $1 \text{ minute} \cdot 58.8 \text{ metres} \cdot \text{min}^{-1} * 1600 \text{ metres} \cdot \text{mile}^{-1} * 2.4 \text{ miles}$
 $= 65.3 \text{ minutes}$

APPENDIX B

Sample calculation for the estimation of time in the cycling component of the Ironman triathlon.



The above graph indicates the time of occurrence of T_{VENT} . Unfortunately, velocity cannot be readily determined therefore a series of stages were incorporated to estimate this value.

Stage 1:

A relationship was developed between Excess CO_2 at T_{VENT} and mph in a short course triathlon (1991 English Bay Triathlon). This variable was chosen based on several studies that have shown its strong relationship to performance in endurance sports (Langill and Rhodes, 1992; Loat and Rhodes, 1991; Rhodes and McKenzie, 1984). A separate subject pool was used and the following linear regression was developed:

$$\text{mph} = (\text{EXCO}_2 * 0.845) + 12.07 \quad r = 0.68$$

Stage 2:

Since this equation was being developed in one subject pool and used in another it was desired that the measured variable show similar values for both populations. An ANOVA comparing Ironman and English Bay triathletes found a nonsignificant difference between excess CO_2 used in the prediction equation but a significant difference in speed (in mph).

T_{VENT} VARIABLE	t	p value
EXCO_2	1.93	> 0.05

This necessitated some form of correction for the differences in speed between cycling 40 km and cycling 112 miles in a triathlon.

Stage 3:

A sample of 26 subjects made up of males in the same age category as this study who took part in both events was determined. A linear regression was performed to relate mph in the Ironman cycling to mph in the English Bay cycling. This equation was then used as a speed correction factor:

$$\text{mph (112 mile)} = (\text{mph (40 km)} * 0.9988) - 3.35r = 0.91$$

Stage 4:

These equations were then used to determine mph at T_{VENT} for the Ironman subjects as follows:

$$\text{eg: EXCO}_2 \text{ at } T_{\text{VENT}} = 11.54$$

$$\begin{aligned}\text{mph at } T_{\text{VENT}} &= (11.54 * 0.845) + 12.07 \\ &= 21.82 \text{ mph (uncorrected for speed difference)}\end{aligned}$$

$$\begin{aligned}\text{mph (112 mile) at } T_{\text{VENT}} &= 21.82 * 0.9988 - 3.35 \\ &= 18.4 \text{ (corrected for speed difference)}\end{aligned}$$

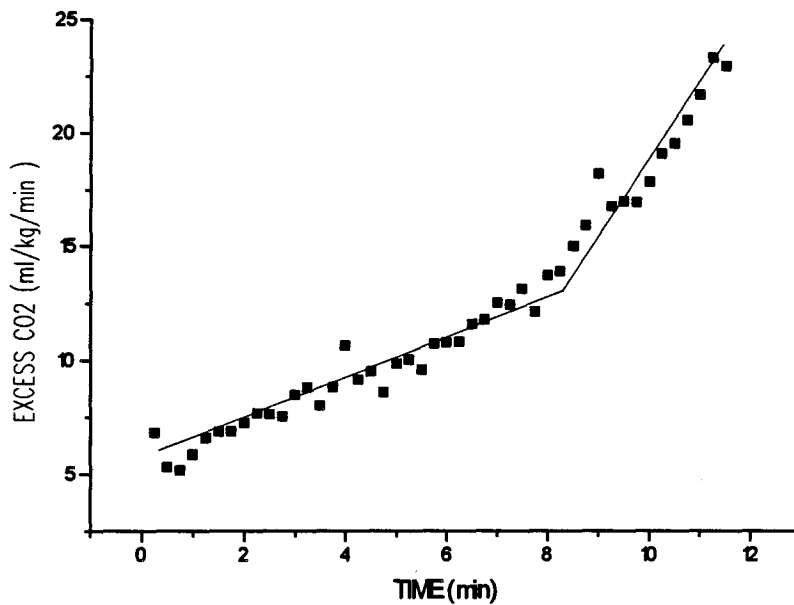
Stage 5:

Mph were then converted to time using the distance for this component of the triathlon:

$$112 \text{ miles} \cdot 18.4 \text{ mph}^{-1} * 60 \text{ min} \cdot \text{hr}^{-1} = 364.4 \text{ min (6:04)}$$

APPENDIX C

Sample calculation for the estimation of time in the running component of the Ironman triathlon.



1) In the graph of excess CO₂ vs. time each minute corresponded to a different treadmill velocity

eg: minute 8 = 8.5 mph

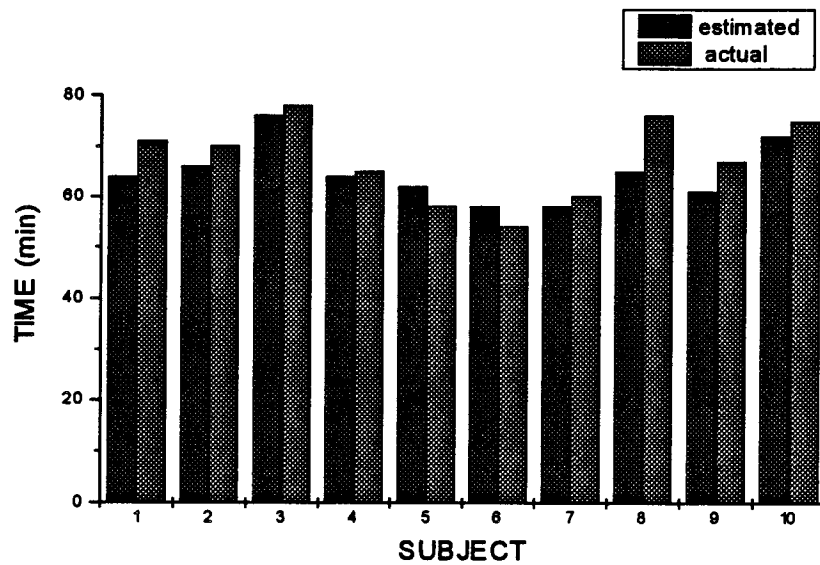
2) Mph at the threshold was then converted to minutes since the distance of the run component was known (26.2 miles)

$$26.2 \text{ miles} \cdot 8.5 \text{ mph}^{-1} \cdot 60 \text{ min} \cdot \text{hr}^{-1} = 185 \text{ min (3:05)}$$

APPENDIX D

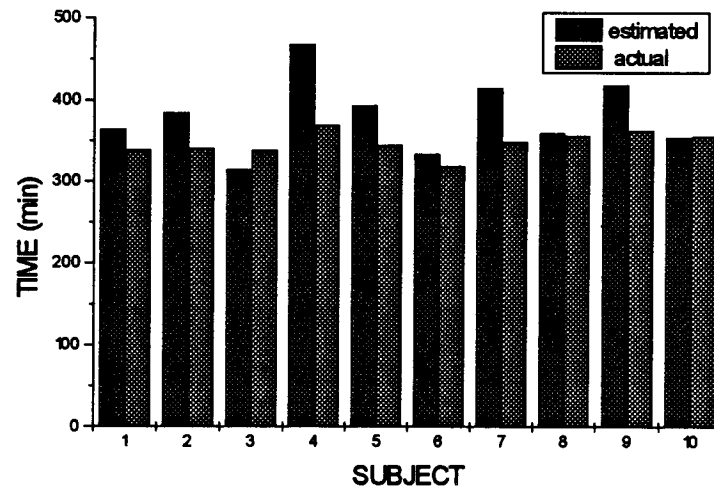
Individual data comparing estimated and actual times for swimming, cycling, and running.

1) Swim times (minutes) for individual subjects.



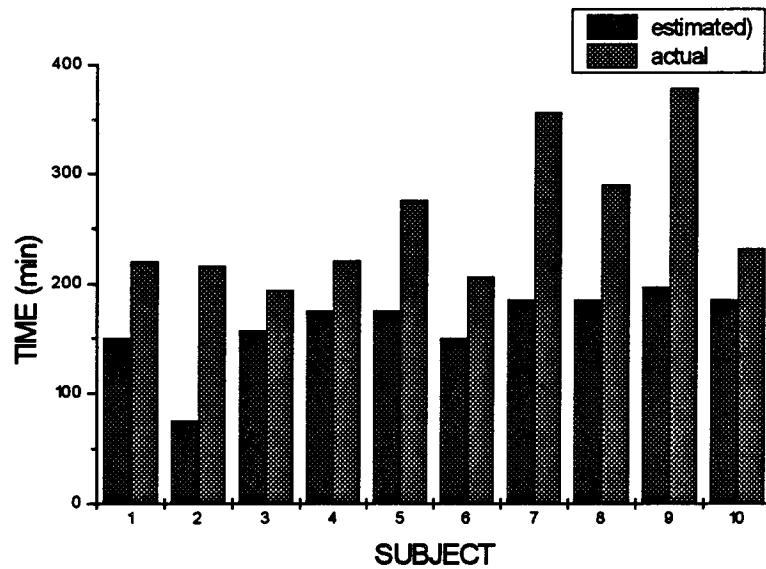
SUBJECT	1	2	3	4	5	6	7	8	9	10
ESTIMATED	64	66	76	64	62	58	58	65	61	72
ACTUAL	71	70	78	65	58	54	60	76	67	75

2) Cycle times (minutes and hours:minutes) for individual subjects.



SUBJECT	1	2	3	4	5	6	7	8	9	10
ESTIMATED	6:04	6:24	5:14	7:47	6:33	5:33	6:54	5:59	6:58	5:54
ACTUAL	5:39	5:40	5:38	6:08	5:44	5:18	5:48	5:56	6:02	5:55

3) Run times (minutes and hours:minutes) for individual subjects.



SUBJECT	1	2	3	4	5	6	7	8	9	10
ESTIMATED	2:30	2:55	2:37	2:55	2:55	2:30	3:05	3:05	3:17	3:05
ACTUAL	3:40	3:36	3:14	3:41	4:35	3:26	5:56	4:49	6:18	3:51

APPENDIX E

Mechanisms of Lactate and Ventilatory Threshold

The recognition by Owles (1930) that there was a critical exercise intensity above which there was accumulation of blood lactate, combined with increased CO₂ excretion and ventilation is the beginning of what would become the anaerobic threshold concept. It is hypothesized that above this "critical intensity" there is a failing of the cardiovascular and/or the respiratory response to supply the energy demanded through the aerobic pathways resulting in work capacity being limited (Knuttgen, 1962). Theoretically, at the anaerobic threshold point work may be performed for indefinite durations since aerobic energy sources are supplying the required energy and waste products are being adequately removed. Thus, the mechanisms responsible for threshold are those which limit aerobic performance and, in some way, control the relationship between endurance capacity and induced fatigue. The determination of this point by invasive and noninvasive means and their underlying mechanisms are the source of considerable debate.

One of the predominant categories of threshold determination involves the invasive measurement of lactate. Lactate is produced to supplement the aerobic energy supply and its presence in the bloodstream reflects increased reliance on the glycolytic pathways of energy production (Jones and Ehrsam, 1982). If there is an imbalance between pyruvate formation and its oxidation in the Krebs's Cycle a subsequent conversion to lactic acid will occur to allow for the continuation of glycolysis (Stainsby, 1986; Jones, 1980). The lactate formed in the dissociation of lactic acid provides a source of fuel (Anderson and Rhodes, 1989) to the working muscle and other tissues of the body.

In progressive intensity exercise there is an initial rise in blood lactate (Brooks, 1986) which is maintained (or slightly increased) until a point where there is a disproportional or abrupt increase in concentration. Whether tissue hypoxia is accompanying this increase in lactic acid production is still questioned (Brook, 1985; Gollnick et al., 1986; Wasserman et al., 1986). It is speculated that this point represents an imbalance in lactate production and removal resulting in an increased reliance on anaerobic metabolism and the release of lactate into the blood (Davis et al., 1983). If the biproducts of lactic acid are allowed to accumulate within the working tissues there will be a rapid onset of fatigue (Anderson and Rhodes, 1989). Increased lactate production results in an increased hydrogen ion release, decreasing muscle and blood pH (Wenger and Reed, 1976) which would limit energy production by anaerobic glycolysis (Hultman and Sahlin, 1980). The fatigue accompanying decreased cellular pH may be the result of an alteration in the membrane permeability or interference with calcium ion binding at the actomyosin binding sites (Wenger and Reed, 1976).

The actual lactate threshold (T_{LAC}), determination based on these mechanisms, has involved several methodologies. T_{LAC} has been characterized by an absolute blood lactate concentration of 2mmole (Hughson et al., 1982) or 4mmole (Sjodin and Jacobs, 1981), an increase above resting levels (Wasserman et al., 1973) and that point where there is an abrupt increase in lactate accumulation (Aunola and Rusko, 1984). Most of the methods are not without controversy, particularly the absolute blood lactate concentrations which have been questioned by several researchers (McLellan and Jacobs, 1989; Stegmann and Kindermann, 1982) on the basis of individual lactate kinetics.

The other predominant category for threshold determination is based on noninvasive ventilatory parameters. The prime stimulators of ventilation

accompanying increasing levels of exercise are increased CO_2 production, an associated fall in blood bicarbonate due to buffering of metabolic acids, and a rise in arterial pH (Anderson and Rhodes, 1989). Changes in breathing rate and depth are made to provide a matching of alveolar ventilation to blood perfusion (Sutton and Jones, 1979). Ventilation is strongly linked to CO_2 output (Wasserman and Whipp, 1975) with the relationship demonstrating ventilation increases in proportion to CO_2 production (Swanson, 1979). Prior to the threshold, CO_2 production will rise in response to the aerobic metabolism of fats and carbohydrates. Above the threshold, in this case ventilatory threshold (T_{VENT}), there will be an increased CO_2 load resulting from the production and buffering of lactic acid by bicarbonate as follows:



Thus, above T_{VENT} increases in ventilation above those responsible for arterial CO_2 compensation do not allow for the complete compensation for the pursuing lactic acidosis (Wasserman and Whipp, 1975). An independent ventilatory stimulus is created to increase ventilation and lower the hydrogen ion content of the blood. This will result in a constraining of the buffering capacity of the blood and pH will drop (Whipp et al., 1980) with the accompanying "fatigue" results already discussed.

The ability to use ventilatory measures to represent invasive changes has received considerable attention. While Powers et al. (1984) were not able to produce high correlations and concluded that T_{LAC} could not be accurately determined by gas exchange variables several other researchers have employed T_{VENT} with considerable success (Wasserman et al., 1973; Clode et al., 1969; Anderson and Rhodes, 1991). Again, as with T_{LAC} , considerable variability exists with respect to the different methods of detection. Caiozzo et al. (1982) found R to be the least sensitive, with \dot{V}_E , $\dot{V}_E/\dot{V}\text{O}_2$, $\dot{V}\text{CO}_2$ to all provide

excellent predictions of T_{LAC} . One other measure used in detection has produced very strong links to performance (Rhodes and McKenzie, 1984; Hearst and Rhodes, 1982; Loat and Rhodes, 1991). It has been found that the nonmetabolic (excess) CO_2 , resulting from the buffering of lactate, will be generated as long as the rate of lactic acid production is increasing as this will mean additional hydrogen ions to buffer (Wasserman et al., 1986). While the hydrogen ion and CO_2 within the muscle readily diffuse into the bloodstream the lactate molecule has a translocation hindrance to its movement out of the muscle (Stainsby, 1986). This may result in increases in excess CO_2 being detected before a significant rise in blood lactate, allowing excess CO_2 to more accurately reflect cellular lactate production and accumulation (Issekutz and Rodahl, 1961). Volkov et al. (1975) found the excess CO_2 "index" to directly relate to the magnitude of lactate production through the glycolytic pathway and the organism's buffering processes. Further investigation by Langill and Rhodes (1992) found that a strong relationship exists between excess CO_2 and blood lactate ($r=0.92$) and that their respective curves over time with increasing exercise parallel one another.

Despite the controversy surrounding T_{LAC} and T_{VENT} there is considerable support for the concept (Wasserman et al., 1986; Davis, 1985). While many of the exact mechanisms are still being questioned, the inconclusive results are more likely a result of the need for further research, particularly the intracellular events that these thresholds are based on.