PHYSIOLOGICAL PREDICTORS OF TRIATHLON PERFORMANCE

by

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We accept this thesis as conforming
to the required standard

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Abstract

The purpose of this study was to characterize competitive triathletes and investigate whether selected physiological variables were related to performance in each discipline and overall in a triathlon. Eighteen male and seven female triathletes (mean body mass = 71.5 ± 2.2 kg, mean height = 176.2 ± 1.7 cm, mean body fat percentage = 16.7 ± 1.4) competed in a short course triathlon (1.0 km swim, 30 km cycle and 9 km run) and underwent a battery of physiological tests within a 14 day period. $\dot{V}O_2$ max, economy of movement and ventilatory theshold (VT) were measured on a cycle ergometer (CE), treadmill (TM)and tethered swim apparatus (TS). Leg flexion/extension strength was assessed on a Cybex Isokinetic Dynamometer (30 degrees * s^{-1}).

On the TM both $\dot{V}O_2$ max (60.3 ± 1.6 ml * kg^{-1} * min^{-1}) and the percentage of $\dot{V}O_2$ max at which VT occurred (85.0 ± 1.1) was greater ($p < .001$) than on the CE ($\dot{V}O_2$ max = 57.6 ± 1.5 ml * kg^{-1} * min^{-1}, VT = 79.6 ± 1.2 %), and the values on the CE were greater ($p < .001$)than those measured on the TS ($\dot{V}O_2$ max = 46.6 ± 1.6 ml * kg^{-1} * min^{-1}, VT = 72.8 ± 1.9 %). $\dot{V}O_2$ max values in each exercise mode were above values reported for untrained individuals but below values reported for single sport endurance athletes. The specific energy cost of activity (Economy) was found to be 0.15 ± 0.01 ml of O_2* kg of body mass^{-1} * kg of load^{-1} for swimming, 0.21 ± 0.00 ml * W^{-1} for cycling and 0.21 ± 0.00 ml * kg^{-1} * m^{-1} for running. Absolute / relative leg extension strength was 191.1 ± 10.4 N·m / 2.62 ± 0.1 N·m * kg $^{-1}$ and absolute / relative leg extension strength was 122.2 ± 6.9 N·m / 1.67 ± 0.1 N·m * kg^{-1}.

Triathlon swim time was best predicted by linear regression of relative swim $\dot{V}O_2$ max and the specific energy cost of swimming ($R^2 = 0.72$). The best predictors of triathlon cycling time were either absolute cycle $\dot{V}O_2$ max or power output at VT on the CE, ($R^2 = 0.52$), and no combination of variables significantly improved prediction of cycling time. Similarly the velocity at running VT was the best predictor of run time ($R^2 = 0.79$). Overall triathlon time was significantly correlated to measures of $\dot{V}O_2$ max and VT in each exercise mode suggesting that specific training in each exercise mode is of importance. The specific energy cost of swimming and running velocity at VT were the best predictors of overall performance ($R^2 = 0.90$). That swimming economy is a strong predictor of overall performance when the swim accounts for only 15 % of total triathlon time suggests a residual effect of swimming on cycling and running performance. A triathlete with a

higher velocity at run VT than their competitor should be able to run faster at the same muscle pH, or have a higher muscle pH at the same absolute run velocity. During the later stages of the race this may have a large impact on overall performance.

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Acknowledgements

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INTRODUCTION

The triathlon incorporates the disciplines of swimming, cycling and running and requires that these events are completed in an uninterupted sequence. Distances range from the standard short course triathlon format of a 1.5 km swim, 40 km cycle and 10 km run to the ultradistance triathlon consisting of a 3.9 km swim, 180.2 km cycle and 42.2 km run (marathon). Unlike athletes that train for only one event, eg. cyclists, triathletes must train simultaneously for three events. The effect that this has on the physiological characteristics of these athletes has been documented in only a few studies (O'Toole et al., 1987a; O'Toole, 1989b; Kohrt et al., 1987a; Holly et al., 1986; Dengel et al., 1989). It is of importance to further document the physiological characteristics of triathletes so as to better understand the implications of simultaneous training in cycling, swimming and running on performance in each of these exercise modes and overall triathlon performance.

Certain physiological variables have been shown to be of importance to endurance performance. Maximal oxygen consumption ($\dot{V}O_2$ max) is a measure of the rate at which energy can be released exclusively from oxidative processes (Thoden et al., 1983; p 39). Several researchers have found $\dot{V}O_2$ max to be a relatively good predictor of performance, especially when used in conjunction with other information such as body composition, muscle fiber type, muscular strength and endurance, efficiency and biomechanics (Foster & Daniels, 1975; Burke, 1980; Faria, 1984; Wilmore & Brown, 1974). Others have found no significant relationship between $\dot{V}O_2$ max and endurance performance (Vrijens et al., 1982, Hagberg et al., 1979).

Only two studies report on the relationship of $\dot{V}O_2$ max to triathlon performance (Kohrt et al., 1987a; O'Toole et al., 1987b). The former study related cycling $\dot{V}O_2$ max to cycle performance in a half - distance Ironman triathlon, while the latter described cycling $\dot{V}O_2$ max in relation to overall finish time in the Hawaii Ironman Triathlon. Both studies reported weak correlations of $\dot{V}O_2$ max with performance.

Anaerobic threshold (AT) has also been demonstrated to be related to endurance performance. Wasserman and McIlroy (1964) defined AT as the power output that marked the transition from aerobic energy supply to anaerobiosis and considered lactate threshold and ventilatory threshold to be manifestations of anaerobiosis in the muscle. They hypothesized that the formation of hydrogen ion through anaerobiosis caused an increase in PCO_2 through the bicarbonate buffering system, which stimulated ventilation.

Others have shown however that the lactate and ventilatory thresholds are coincidental and not reflective of the same mechanism since they may be dissociated when training (Gaesser & Poole, 1986) and testing protocols (Green et al., 1983) as well as substrate availability (Neary et al., 1985) are varied. The oxygen cost that triggers greater recruitment of fast twitch motor units has been suggested to be the stimulus for ventilatory threshold (Neary et al., 1985) and has also been hypothesized to coincidentally elicit increased lactate production (Neary et al., 1985). Confirmation of these hypotheses would explain the simultaneous appearance of the lactate and ventilatory thresholds.

$\dot{V}O_2$ at AT has been significantly related to distance running success (Tanaka et al., 1984; 1986) as have variables thought to be related to AT such as ventilatory threshold (VT) (Perronet et al., 1987) and fractional utilization of $\dot{V}O_2$ max (Costill et al., 1971). Percent $\dot{V}O_2$ max at lactate threshold (LT) has also been related to endurance performance in trained cyclists (Coyle et al., 1988), however no research reporting AT measures in swimmers has been reported and little work in this area has been completed with triathletes. O'Toole et al. (1988) found that oxygen uptake at the lactate and ventilatory thresholds was poorly related to bike finish time ($r = -0.37$ and -0.26 respectively), as was fractional utilization of $\dot{V}O_2$ max, heart rate and percentage of maximum heart rate at the LT or VT (r = - 0.01 to - 0.05). In submaximal exercise $\dot{V}O_2$ increases linearly with power ouput (Astrand & Rodahl, 1977) assuming that the efficiency of movement is similar (Kearney & Van Handel, 1989). In the above study this was assumed since AT was not expressed as a power output. Expressing AT as a power output may be more relevant to performance since economy is accounted for. A high power output at AT would enable the triathlete to do more work, eg. go faster than an opponent with a lower power output at AT, without producing high amounts of lactic acid and thereby accelerating the fatigue process. This has not been investigated in triathletes.

The economy of movement has been suggested as a discriminating factor in endurance type performance . Kearney and Van Handel (1989) defined economy as the metabolic cost in ml of O_2 * kg of body mass $^{-1}$ * min $^{-1}$ of performing an activity at a standard predetermined submaximal intensity. They also described a variation of this, the specific energy cost of transport, which expresses metabolic cost relative to distance (eg. ml * kg $^{-1}$ * m $^{-1}$). A more economic endurance athlete uses less energy than a less economic counterpart at a standard power output, and is therefore able to a) move faster or b) conserve energy for use in the later stages of an endurance activity. Many indexes of economy have been shown to be related to endurance performance in the sports of running (Daniels, 1974; Costill et al., 1971; Housh et al., 1988), cycling (Coyle et al., 1988) and swimming (Montpetit et al., 1988; Lavoie & Montpetit, 1986; Miyashita, 1978; Touissant et al., 1988; Costill et al., 1985; Van Handel et al., 1988). Although it seems logical that the economy of movement in swimming, cycling and running may relate to triathlon performance this question remains open.

Strength, the peak force a muscle is able to generate (Sale & Norman, 1983), has been hypothesized to have an effect on endurance performance (Edington & Edgerton, 1976; p 276). Hickson et al. (1988) trained the leg musculature 3 days/week for 10 weeks and increased mean leg strength by 30 percent, without changing $\dot{V}O_2$ max in cycling or running. Cycling and running endurance performance were improved by 11 and 13 percent respectively at a power output that elicited exhaustion in 5 - 8 minutes. Longer term endurance, a power output on the bike eliciting fatigue around 70 minutes, and a 10 km run, was improved on the bike by 20 percent however was not improved in running. Since the leg musculature is utilized in all three triathlon disciplines it may be hypothesized that increased leg strength would be beneficial to triathlon performance.

Considering that the physiology of triathletes is still not well understood, and that little is known about the relationship of physiological variables to triathlon performance the purposes of this study were:

1) To characterize VT in triathletes for each mode of exercise (swim, cycle,run) and relate these values to performance time in each leg of a short course triathlon as well as overall performance time.

2) To investigate the aerobic power characteristics of triathletes for each mode of exercise and relate relative and absolute scores to performance as above.

3) To assess the economy of movement in each mode of exercise and relate these to performance as above.

4) To characterize isokinetic strength values for knee extension and flexion in triathletes and relate these to performance as above.

5) To develop a multiple linear regression model for prediction of overall triathlon performance as well as performance of the swim, run and cycle legs using selected physiological and anthropometric variables.

OPERATIONAL DEFINITIONS

1) Endurance athlete - any athlete that trains for an event requiring prolonged work (> 15 minutes) at a submaximal power output, eg. marathoner.

2) Triathlete - an endurance athlete training to perform in the swim, cycle and run modes of exercises simultaneously.

3) Performance - The time taken to complete a particular phase of a triathlon, or endurance race. Shorter times represent better performance.

4) Anaerobic threshold (AT) will refer to ventilatory threshold (VT) which will be taken as the power output at which minute ventilations ($\dot{V}e$) begin to increase non-linearly with respect to power output and oxygen consumption ($\dot{V}O_2$).

5) Maximal Oxygen Consumption ($\dot{V}O_2$ max) - The highest $\dot{V}O_2$ value obtained in an incremental continuous loading protocol. Termination criteria will be a combination of the following: 1) a plateau in $\dot{V}O_2$ increase (< 2 ml * kg^{-1} * min^{-1}); 2) an $R \geq 1.15$; 3) attainment of maximum heart rate; 4) volitional exhaustion.

METHODS

SUBJECTS

Eighteen male and seven female triathletes (Age 19+) with a mean body mass of 71.5 ± 2.2 kg, a mean body height of 176.2 ± 1.7 cm and a mean percent body fat of 16.7 ± 1.4 % were familiarized with the testing procedures, equipment and nature of the study prior to signing informed consent (Appendix A) and agreeing to participate. They were randomly split into two groups(A and B) for testing purposes.

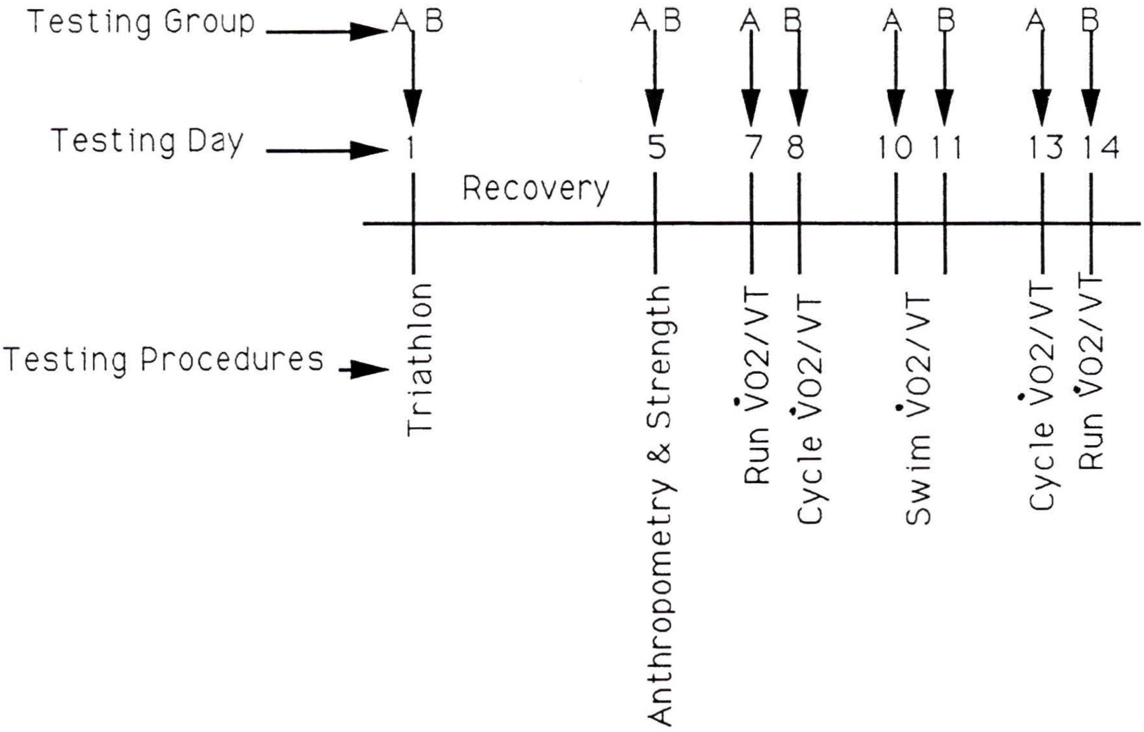
TESTING PROCEDURE

The experimental testing period bracketed 14 days and included a short course triathlon, strength testing and VT/$\dot{V}O_2$ max testing on the tethered swim apparatus, cycle ergometer and treadmill (Figure 1).

THE TRIATHLON

Subjects competed in a triathlon (1.0 km swim, 30 km cycle, 9.0 km run) on day 1 of the testing period. Their completion time for the swim, cycle and run portions of the race was taken from the time the subjects started or left he

Figure 1: Testing schedule of the triathletes (Groups A & B) over the two week study period.


Testing Group
A B
A B
A B
A B
A B
Testing Day
1
5
7 8
10 11
13 14
Recovery
Testing Procedures
Triathlon
Anthropometry & Strength
Run V̇O2/VT
Cycle V̇O2/VT
Swim V̇O2/VT
Cycle V̇O2/VT
Run V̇O2/VT

transition area until they entered the next transition area or finished.

Days 2 - 4 were designated triathlon recovery days. To facilitate recovery subjects were instructed to abstain from intense exercise, avoid alcohol, drink at least 15 glasses of water per day and consume mainly complex carbohydrates. The testing group was then split randomly into two groups with group A reporting on days 7, 10 and 13 and group B reporting on days 8, 11 and 14.

STRENGTH TESTING

Day 5 consisted of the anthropometric measures body mass, height and percent body fat (Durnin & Womersley, 1974; p95), followed by isokinetic strength measurements of leg extension and flexion at 30 degrees per second on the Cybex Isokinetic Dynamometer. For the strength testing, the subjects upper body was restrained using straps to facilitate isolation of the quadriceps and hamstring muscles. 4 - 5 warm-up contractions were followed by 60 seconds of passive rest and then four maximal contractions. The units of measurement were newton-meters (Nm) and Nm * kg of body mass $^{-1}$.

VT AND $\dot{V}O_2$ max TESTING

For all VT/$\dot{V}O_2$ max tests a Beckman Metabolic Measurement Cart calibrated before each test with known concentrations of primary standard calibration gas was used to give respiratory and metabolic measures every 20 seconds (volume of air expired per minute [$\dot{V}e$] , volume of O_2 consumed per minute [$\dot{V}O_2$], volume of CO_2 consumed per minute [$\dot{V}CO_2$], fraction of expired CO_2 [$FeCO_2$], fraction of expired O_2 [FeO_2], and respiratory quotient [$R = \dot{V}CO_2 * \dot{V}O_2{}^{-1}$]). Sportester PE 3000 heart rate monitors were used to monitor heart rate via telemetry.

Tests in each exercise mode were separated by 72 hours and were administered in the order of run-swim-cycle for group A and cycle-swim-run for group B to minimize any ordering effect the testing may have had. A continuous incremental test was used to measure both VT and $\dot{V}O_2$ max for tethered swim, cycle ergometry and the treadmill. For each mode of exercise the highest $\dot{V}O_2$ value obtained during a test was taken as $\dot{V}O_2$ max. The criteria for the determination of $\dot{V}O_2$ max was a combination of the following: 1) a plateau in $\dot{V}O_2$ increase (< 2 ml/kg/min) or an increase smaller than that expected with an increase in load; 2) an R 1.15; 3) attainment of maximum heart rate; 4) volitional exhaustion. AT was measured using ventilatory threshold (VT) and the criteria for the determination of

VT was a non-linear increase in $\dot{V}e$ vs $\dot{V}O_2$. To determine VT a computerized algorithm technique was used that searches for the breakpoint value in $\dot{V}e$ vs $\dot{V}O_2$ by minimizing the residual sum of squares in a linear regression (Jones & Molitoris, 1984).

ANALYSIS OF ECONOMY OF MOVEMENT

The specific energy cost of transport in each exercise mode was calculated as a measure of economy. In tethered swimming the O_2 cost in ml * kg of body mass $^{-1}$ * kg of load pulled $^{-1}$ was calculated at a load of 4 kg; in cycling the oxygen cost in ml * Watt $^{-1}$ at a load of 3 kg was calculated; and ml of O_2 used * kg of body mass $^{-1}$ * m $^{-1}$ was calculated at a treadmill speed of 8 mph while running.

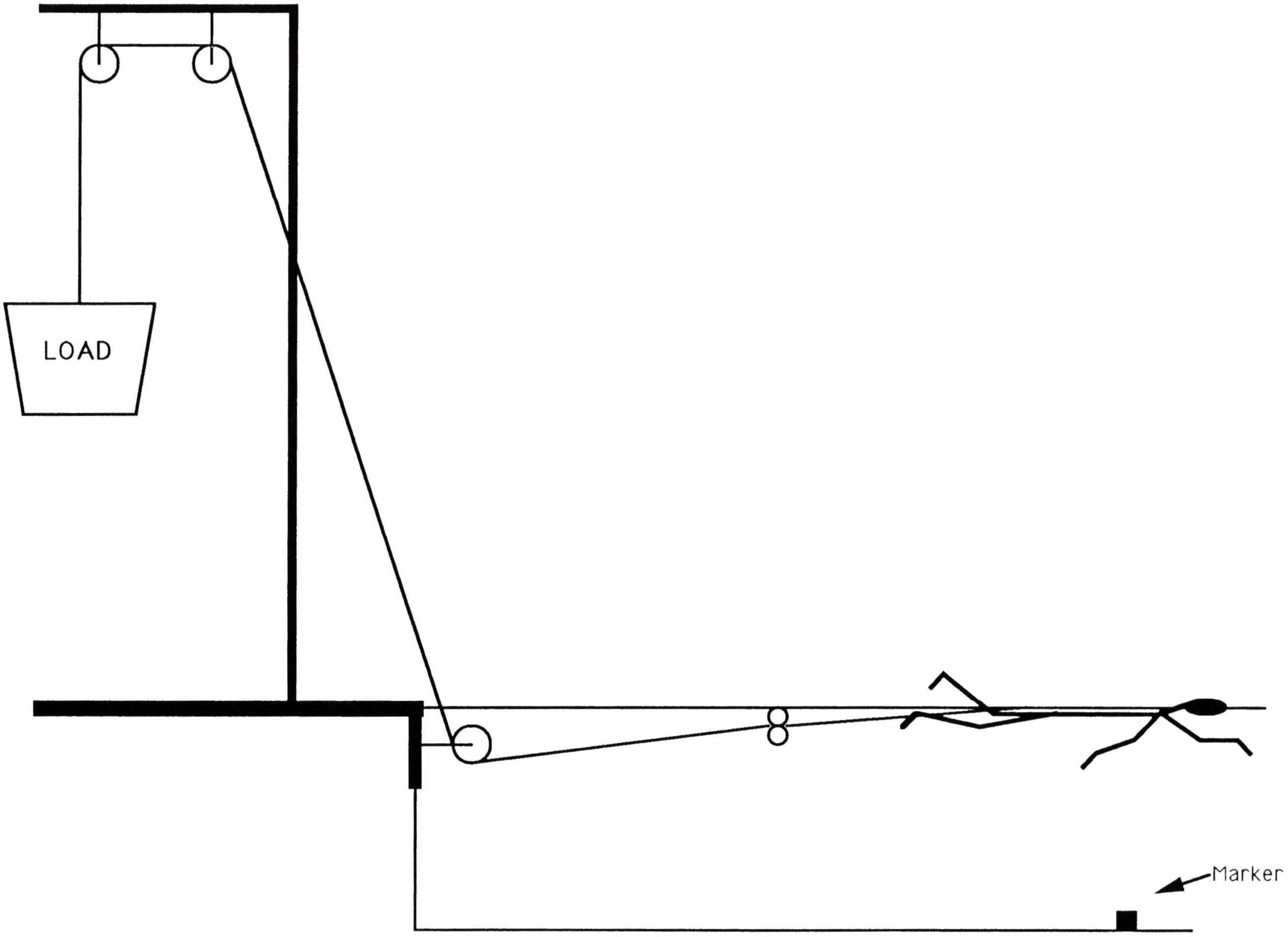
TREADMILL TESTING

Days 7 and 14 consisted of treadmill VT/$\dot{V}O_2$max tests. A continuous incremental protocol was used which increased the velocity by 1 mph every two minutes until estimated race pace was obtained and then increased the grade by 2 % every minute until $\dot{V}O_2$ max or volitional exhaustion was reached.

TETHERED SWIM TESTING

Days 10 and 11 were used to conduct tethered swim (Figure 2) VT/$\dot{V}O_2$ max tests. The continuous incremental

Figure 2: The tethered swim apparatus.


LOAD
Marker

protocol consisted of a 3 kg warm-up load for males and a 2 kg warm-up load for females followed by an increase of 250 grams every 2 minutes until VT was estimated from respiratory variables. 500 gram load increases were then administered every minute until the swimmer could no longer maintain their place in the water or sustain bouyancy. At all times a lifeguard was present and a spotter present in the water to communicate with the swimmer.

CYCLE ERGOMETER TESTS

Days 8 and 13 consisted of cycle VT/$\dot{V}O_2$ max tests. The tests were performed on a Monark friction cycle ergometer equipped with racing bars and toe clips. The continuous incremental protocol consisted of a 3 min warm-up at approximately 140 W (2Kp @ 70 rpm) followed by 35 W increments every 2 minutes thereafter until VT was estimated from respiratory variables. 70 W load increases were then administered every minute until $\dot{V}O_2$ max or volitional exhaustion was reached.

STATISTICS

The SAS-PC statistical package (Release 6.03) was used for all statistical analyses. The physiological characteristics of the triathletes are described using the descriptive statistics mean and standard error of the mean.

A One- Way Analysis of Variance (ANOVA) was used to establish if any significant differences existed in the quality of performance in each phase and overall in the triathlon. Multivariate Analysis of Variance (MANOVA) followed by a step down to ANOVA and post-hoc t-tests were used to determine the difference between the physiological measures VT and $\dot{V}O_2$ max and mode of exercise.

To determine the relationships between the individual physiological variables tested and performance in each leg of the triathlon as well as overall performance, Pearson Product-Moment correlations were used. Multiple linear regression was used to determine the best combination of variables for performance prediction in the swim/cycle/run legs and the overall triathlon. Firstly, the R Square procedure (Myers, 1986) was used to determine alternative 3 variable subsets which accounted for similar amounts of variance in the prediction of completion time in each phase and overall in the triathlon. Secondly the best five models for each of these were entered into forward regression in order that the significance of each predictor variable could be calculated and the best fit model determined.

RESULTS

Figure 3 shows the percent of overall time accounted for by each phase of the triathlon and table 1 shows mean performance times and the percentage of the mean group completion time spent by the fastest competitor for the swim, cycle, run legs, and overall in the triathlon. Group performance level was of the same quality for each component of the triathlon since the percentage of the groups completion time spent by the fastest competitor showed no significant differences between swim, cycle, run or overall performance as tested with a 1-way ANOVA.

Absolute and relative $\dot{V}O_2$ max values for swim, cycle and run exercise modes are reported in table 2. Absolute $\dot{V}O_2$ at VT, relative $\dot{V}O_2$ at VT, load at VT and the percentage of $\dot{V}O_2$ max at which VT occurred for each exercise mode is reported in table 3. On the treadmill both $\dot{V}O_2$ max (Figure 4) and percentage of $\dot{V}O_2$ max at which VT occurred (Table 3)was greater ($\underline{p} < .001$) than on the cycle ergometer, and the cycle ergometer values were greater ($\underline{p} < .001$) than those measured while tethered swimming.

The specific energy costs of transport was found to be 0.15 ± 0.01 ml $*$ kg $^{-2}$ for swimming, 0.21 ± 0.00 ml $*$ W $^{-1}$ for cycling and 0.21 ± 0.00 ml $*$ kg $^{-1}$ $*$ m $^{-1}$ for running.

Figure 3: The mean percentage of time accounted for by each phase of the triathlon.

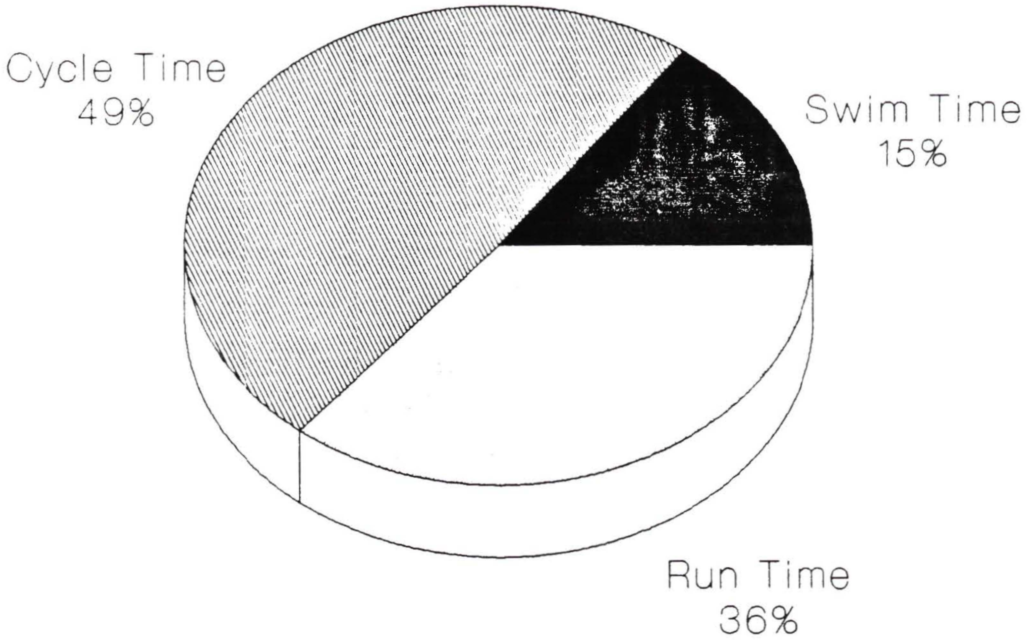

Cycle Time
49%
Swim Time
15%
Run Time
36%

Table 1: Mean (± SE)performance time (s) (PT) and the percentage of time spent by the fastest competitor in relation to the group (% T) for the swim, cycle and run legs and overall in the triathlon.

		Swim	**Cycle**	**Run**	**Overall**
PT	$\bar{X}$	1061	3467	2529	7057
	SE	±50	±88	±68	±181
% T	$\bar{X}$	80.5	82.4	81.2	82.3
	SE	±2.9	±2.0	±2.0	±2.0

Note: N = 25

Table 2: Mean (± SE) absolute ($A\dot{V}O_2$) and relative ($R\dot{V}O_2$) $\dot{V}O_2$ max values for the swim, cycle and run exercise modes.

		Swim	Cycle	Run
$A\dot{V}O_2$ $L*min^{-1}$	$\overline{X}$	3.35^{ab}	4.12^{ac}	4.32^{bc}
	SE	±0.16	±0.16	±0.17
$R\dot{V}O_2$ $ml*kg^{-1}*min^{-1}$	$\overline{X}$	46.6^{ab}	57.6^{ac}	60.3^{bc}
	SE	±1.6	±1.5	±1.6

Note: N = 25

Paired letters indicate that means are significantly different ($p < 0.001$).

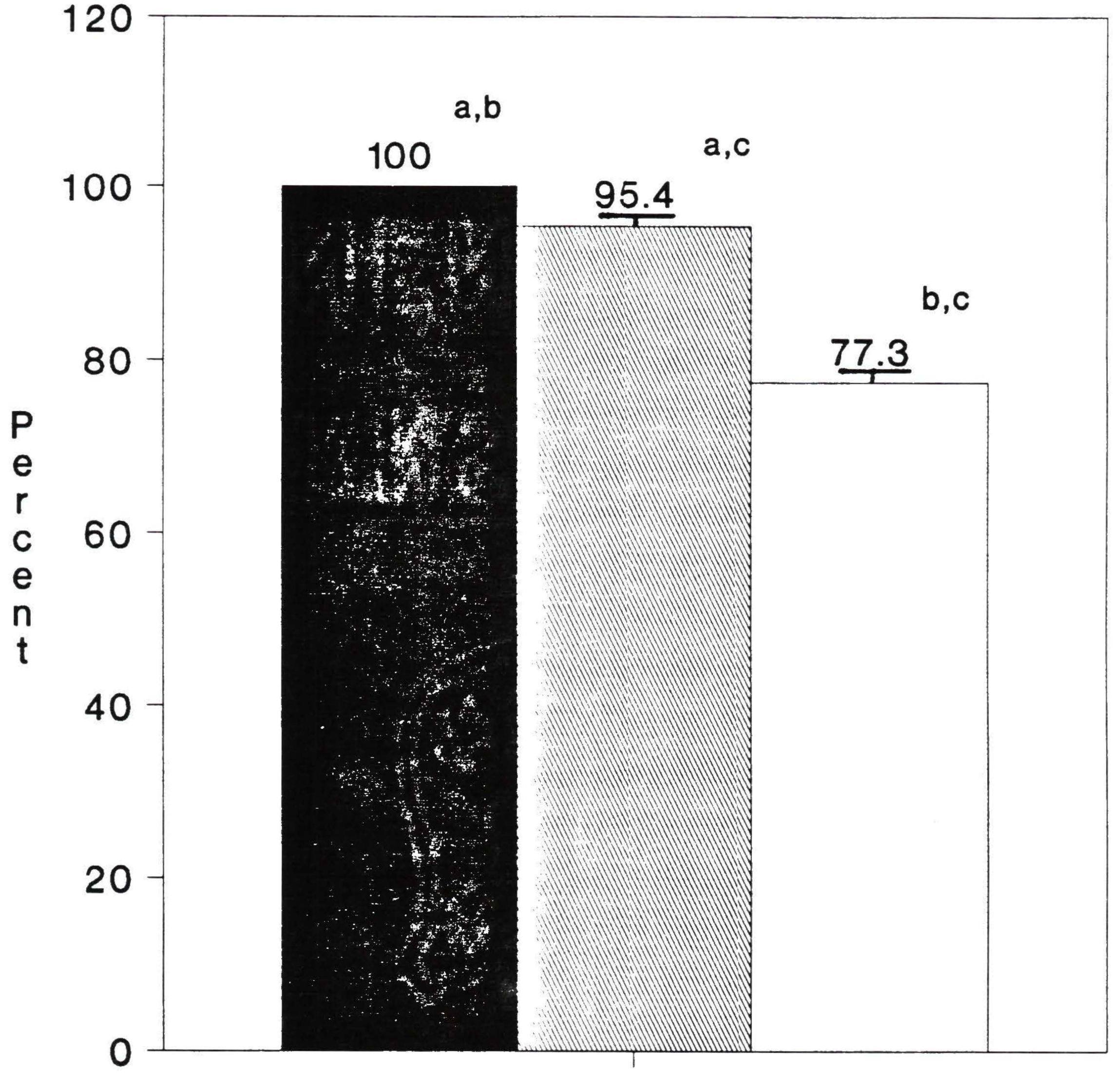
Table 3: Mean (± SE) absolute $\dot{V}O_2$ at VT (AVT), relative $\dot{V}O_2$ at VT (RVT), load at VT (LVT) and percentage of $\dot{V}O_2$ max that VT occurred at (%VT) for swim, cycle and run exercise modes.

		Swim	Cycle	Run
AVT L*min^{-1}	$\overline{X}$	2.40^{ab}	3.30^{ac}	3.67^{bc}
	SE	±0.13	±0.15	±0.15
RVT ml*kg^{-1}*min^{-1}	$\overline{X}$	33.8^{ab}	45.7^{ac}	51.1^{bc}
	SE	±1.3	±1.3	±1.3
LVT	$\overline{X}$	4.0 kg	261.2 W	9.3 m*s^{-1}
	SE	±0.2	±11.4	±0.2
%VT	$\overline{X}$	72.8^{ab}	79.6^{ac}	85.0^{bc}
	SE	±1.9	±1.2	±1.1

Note: N = 25

Paired letters indicate that means are significantly different ($p < 0.001$)

Figure 4: The mean (± SE) percentage of run $\dot{V}O_2$ max achieved for cycle and swim $\dot{V}O_2$ max.



Note: paired letters indicate that means are significantly different ($p < 0.001$)

Mean absolute leg extension strength was 191.1 ± 10.4 Nm and when expressed relative to body mass was 2.62 ± 0.1 Nm * kg $^{-1}$. Mean absolute leg flexion strength was 122.2 ± 6.9 Nm and relative leg flexion strength was 1.67 ± 0.1 Nm * kg $^{-1}$.

The correlations of the physiological variables with swim, cycle, run and overall completion time are reported in tables 4 - 7 respectively. For swimming time and overall time multiple linear regression equations had significantly higher predictive power than simple correlations. For running and cycling the multiple regression did not add predictive power to the simple correlations. Both simple and multiple regression prediction equations for swim, cycle, run and overall triathlon time are reported in figure 5.

Table 4: Intercorrelations of selected physiological variables and triathlon swim time.

	1	2	3	4	5	6	7	8	9
1 Height									
2 Mass	.84 ***								
3 % BF	-.56 **	-.31							
4 SV̇O2MR	.29	.26	-.66 ***						
5 SVTRES	-.42	.64 ***	-.38	.67 ***					
6 SEC	-.42	-.64 ***	.15	-.33	-.72 ***				
7 LSTFNM	.75 ***	.72 ***	-.58 **	.53 **	.51	-.41			
8 LSTEXNM	.68 ***	.70 ***	-.54 **	.43	.37	-.34	.88 ***		
9 ST	-.20	-.20	.37	-.74 ***	-.70 ***	.56 **	-.36	-.23	

Note: N = 25

$p < .01$ **
$p < .001$ ***

Legend:

Height = Body height (cm)
Mass = Body mass (kg)
% BF = Body fat percentage
SV̇O2MR = Relative swim VO$_2$ max (ml * kg $^{-1}$ * min $^{-1}$)
SVTRES = Resistance pulled at swim VT (kg)
SEC = Specific energy cost of swimming (ml * kg $^{-2}$)
LSTFNM = Absolute flexion strength of the leg (Nm)
LSTEXNM = Absolute extension strength of the leg (Nm)
ST = Time (s) to complete swim leg of triathlon

Table 5: Intercorrelations of selected physiological variables and triathlon cycle time.

	1	2	3	4	5	6	7	8	9
1 Height									
2 Mass	.84 ***								
3 % BF	-.56 **	-.31							
4 CV̇O2MA	.74 ***	.80 ***	-.64 ***						
5 CVTPO	.79 ***	.80 ***	-.64 ***	.92 ***					
6 CEC	-.42	-.28	.49	-.40	-.44				
7 LSTFNM	.75 ***	.72 ***	-.58 **	.72 ***	.80 ***	-.35			
8 LSTEXNM	.68 ***	.70 ***	-.54 **	.65 ***	.74 ***	-.34	.88 ***		
9 CT	-.64 ***	-.60 **	.50	-.72 ***	-.72 ***	.30	-.58 **	-.48	

Note: N = 25

$p < .01$ **
$p < .001$ ***

Legend:

Height = Body height (cm)
Mass = Body mass (kg)
% BF = Body fat percentage
CV̇O2MA = Absolute cycle VO_2 max (L * min $^{-1}$)
CVTPO = Power output at cycle VT (W)
CEC = Specific energy cost of cycling (ml * W $^{-1}$)
LSTFNM = Absolute flexion strength of the leg (Nm)
LSTEXNM = Absolute extension strength of the leg (Nm)
CT = Time (s) to complete cycle leg of triathlon

Table 6: Intercorrelations of selected physiological variables and triathlon run time.

	1	2	3	4	5	6	7	8	9
1 Height									
2 Mass	.84 ***								
3 % BF	-.56 **	-.31							
4 R$\dot{V}$O2MR	.20	.10	-.74 ***						
5 RVTV	.51 **	.42	-.56 **	.71 ***					
6 REC	-.48	-.38	.13	-.02	-.46				
7 LSTFNM	.75 ***	.72 ***	-.58 **	.37	.53 **	-.39			
8 LSTEXNM	.68 ***	.70 ***	-.54 **	.30	.45	-.42	.88 ***		
9 RT	-.51 **	-.41	.60 **	-.64 ***	-.89 ***	.48	-.55 **	-.45	

Note: N = 25

$p < .01$ **
$p < .001$ ***

Legend:

Height = Body height (cm)
Mass = Body mass (kg)
% BF = Body fat percentage
R$\dot{V}$O2MR = Relative run VO_2 max (ml * kg $^{-1}$ min $^{-1}$)
RVTV = Velocity at run VT (m * s $^{-1}$)
REC = Specific energy cost of running (ml * kg $^{-1}$ * m $^{-1}$)
LSTFNM = Absolute flexion strength of the leg (Nm)
LSTEXNM = Absolute extension strength of the leg (Nm)
RT = Time (s) to complete run leg of triathlon

Table 7: Intercorrelations of selected physiological variables and overall triathlon time.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1 Height															
2 Mass	.84 ***														
3 % BF	-.56 **	-.31													
4 LSTFNM	.75 ***	.72 ***	-.58 **												
5 LSTEXNM	.68 ***	.70 ***	-.54 **	.88 ***											
6 RV̇O2MR	.20	.10	-.74 ***	.37	.14										
7 CV̇O2MA	.74 ***	.80 ***	-.64 ***	.72 ***	.65 ***	.63 ***									
8 SV̇O2MR	.29	.26	-.66 ***	.53 **	.43	.81 ***	.70 ***								
9 RVTV	.51 **	.42	-.56 **	.53 **	.45	.71 ***	.75 ***	.72 ***							
10 CVTPO	.79 ***	.80 ***	-.64 ***	.80 ***	.74 ***	.51	.92 ***	.60 **	.67 ***						
11 SVTRES	.47	.64 ***	-.38	.51	.37	.52	.78 ***	.67 ***	.65 ***	.68 ***					
12 REC	-.48	-.38	.13	-.39	-.42	-.02	-.32	-.21	-.46	-.33	-.26				
13 CEC	-.42	-.28	.49	-.34	-.34	-.51	-.40	-.37	-.39	-.44	-.47	-.10			
14 SEC	-.42	-.64 ***	.15	-.41	-.34	-.20	-.58 **	-.33	-.48	-.53 **	-.72 ***	.21	.26		
15 OT	-.56 **	-.50	.57 **	-.59 **	-.46	-.57 **	-.76 ***	-.71 ***	-.91 ***	-.72 ***	-.69 ***	.41	.36	.63 ***	

Note: N = 25 **Legend:** Variables defined in tables 4, 5 and 6.
$p < .01$ ** $p < .001$ ***

Figure 5: Simple and multiple regression equations for the prediction of completion time in each phase and overall in a short course triathlon.

Swim time (s) = 3226.8 (SEC) - 19.6 (S$\dot{V}$O2MR) + 1485.9

R^2 = 0.66

Cycle time (s) = a) -408.1 (C$\dot{V}$O2MA) + 5148.0

b) -5.6 (CVTPO) + 4916.9

R^2 = 0.52

Run Time (s) = -270.0 (RVTV) + 5050.8

R^2 = 0.78

Overall Time (s) = 8424.9 (SEC) -644.6 (RVTV) + 11803.4

R^2 = 0.89

Legend:

SEC = The specific energy cost of swimming (ml * kg^{-2})
S$\dot{V}$O2MR = Relative swim $\dot{V}O_2$ max (ml * kg^{-1} * min^{-1})
C$\dot{V}$O2MA = Absolute cycle $\dot{V}O_2$ max (L * min^{-1})
CVTPO = Power output at cycle VT (W)
RVTV = Velocity at run VT (m * s^{-1})

Discussion

The male triathletes in this study were of similar height (180.0 ± 1.5 cm) to competitive triathletes and single sport endurance specialists in swimming, cycling and running (Table 8). Their body mass (76.2 ± 2.1 kg) was similar to values previously reported for swimmers but heavier than values reported for cyclists, runners and triathletes (Table 8). They also carried more body fat (BF) (13.4 ± 1.0 %) than single sport endurance specialists and triathletes that have been previously studied (Table 8).

The female triathletes were of similar height (166.4 ± 2.1 cm) to triathletes, swimmers, cyclists and runners previously studied (Table 8). Their body mass (59.3 ± 2.1 kg) was in the same range as values previously reported for triathletes, swimmers and cyclists, but heavier than runners (Table 8). Body fat values in the females (25.0 ± 2.0 %) were much higher than values reported for female triathletes, and single sport endurance specialists (Table 8).

The high BF measures in the female triathletes suggest they are at a lower performance level than elite, since the body composition of elite endurance athletes is

Table 8: Anthropometric values reported in the literature for swimmers, cyclists, runners and triathletes

	Height (cm)	Mass (kg)	%BF	References
Swimmers				
Males	175.4 - 182.9	73.7 - 78.2	5.7	19,20,82
Females	166.3 - 174.8	60.9 - 65.8	17.1 - 21.1	53,82
Cyclists				
Males	175.2 - 181.3	65.7 - 72.8	7.1 - 11.6	5,6,24,25,29,30 45,48,90,96
Females	165.0 - 167.7	55.0 - 61.3	15.4	5,6
Runners				
Males	176.6 - 179.3	63.1 - 71.5	4.7 - 12.3	14,36,51,53,67 69,96
Females	165.4 - 169.4	51.6 - 57.2	15.2 - 18.8	14,53,94,95
Triathletes				
Males	173.3 - 179.9	68.9 - 74.5	8.6 - 10.5	7,18,34,43,46, 62,78,92,98
Females	168.5 - 168.9	60.3 -63.1	10.2 - 14.8	36,62,92

characterized by a high lean mass to fat ratio. Male BF measures were only slightly above values previously reported for male endurance athletes. This study was administered in the non - competitive season, which may account for elevated body fat levels due to a seasonal drop in training volume. It is conceivable that, with an increase in training volume during the competitive season, the male triathletes would approach values similar to those previously reported. In support of this hypothesis, the Masters world record holder at Ironman distance stated that his mass was six to seven kg heavier at the time of the study than during his competitive season.

$\dot{V}O_2$ max was measured in each exercise mode of the triathlon. Tethered swim (TS), cycle ergometer (CE) and treadmill (TM) values were similar to those previously reported for triathletes, but lower than values previously reported for endurance specialists in swimming, cycling and running (Table 9). This probably reflects lower training volumes than endurance specialists in each exercise mode. For example, elite cyclists have been reported to train an average distance of 254 km/week (Krebs et al., 1986) while bike training distances for triathletes have been reported between 132 and 227 km/week (Ireland et al., 1987; Zinkgraf et al., 1986; O'Toole, 1989a). Similar relationships may hold for running and swimming.

Table 9: Relative $\dot{V}O_2$ max values (ml * kg $^{-1}$ * min $^{-1}$)for swimmers, cyclists, runners and triathletes.

	Tethered Swim	Cycle Ergometer	Treadmill	References
Swimmers	54.9 - 68.2	--	--	17,20,88
Cyclists	--	61.3 - 74.0	--	4,5,12,29,39 45,48,96
Runners	--	--	64.7 - 79.3	4,9,14,36,51,59 67,73,83,85,94,96
Triathletes	46.8 - 56.7	53.4 - 67.8	57.4 - 68.8	1,17,18,34,42,43,44 46,54,61,62,63

$\dot{V}O_2$ max is known to be a function of the muscle mass engaged in exercise (Gleser et al. 1974). TM $\dot{V}O_2$ max tests elicit higher values than cycling and swimming tests, with cycling tests being 5 - 8 percent lower (Faria, 1984; Saltin & Astrand, 1967; Burke, 1980) and swim tests being 15 - 16 percent lower (Holmer, 1974; Magel, 1974) in untrained subjects. $\dot{V}O_2$ max values for swimmers (Dixon & Faulkner, 1971) and cyclists (Verstappen et al., 1982; Withers et al., 1981; Hagberg et al., 1978) have been reported to exceed treadmill $\dot{V}O_2$ max even though less muscle mass is involved in the exercise. In triathletes swim $\dot{V}O_2$ max has been reported to be between 13 and 25 % lower (Dengel et al., 1989; Kohrt et al., 1987a; 1987b; Kreider et al., 1988) and cycle $\dot{V}O_2$ max 2.3 to 7.0 % lower (Dengel et al., 1989; Albrecht et al., 1986; Kohrt et al., 1987a; 1987b; Millard et al., 1986; O'Toole et al., 1987; Kreider et al., 1988) than run $\dot{V}O_2$ max. In this study, $\dot{V}O_2$ max did decrease in the order of run - cycle - swim and the percentage differences between exercise modes was not consistent with the values reported for untrained subjects but were similar to values previously reported for triathletes. The TS $\dot{V}O_2$ max was 22.7 % and CE $\dot{V}O_2$ max was 4.6 % less than TM $\dot{V}O_2$ max (Figure 4). This may be due to a specificity of training effect for $\dot{V}O_2$ max. Local muscle changes such as increased vascularization (Roberts & Alspaugh, 1974), enhanced aerobic enzyme activities

(Stromme et al. 1977), and increased mitochondrial protein per unit weight of muscle (Morgan, 1971) have been suggested to facilitate both oxygen transport and utilization at the local muscle level, thus possibly explaining the specificity response of $\dot{V}O_2$ max to mode of exercise. In some studies the smaller $\dot{V}O_2$ max differences between exercise modes in triathletes compared to untrained subjects have been attributed to a specificity of training response (Kohrt et al., 1987a; 1987b). In triathletes the range of differences between swim, cycle and run $\dot{V}O_2$ max values reported in the literature is larger than that reported for the untrained population. Since variations in training practices (eg, frequency, intensity and duration in each exercise mode) are likely to have occurred between the various groups of triathletes reported, the large range could also reflect specificity of training responses. However, since training practices were not documented this cannot be substantiated.

In this study $\dot{V}O_2$ at VT, expressed as a percentage of $\dot{V}O_2$ max, increased significantly from TS to CE to TM exercise tests (Table 3). The run and cycle percentages fall within values previously reported for triathletes; however, comparisons can not be made with swim VT since values have not been reported.

Albrecht et al (1986) found VT occurred at 51.6 % of $\dot{V}O_2$ max on the swim bench, 78.8 % on a CE and 79.3 % on a TM while Kohrt et al. (1987a; 1987b) found LT was closer to $\dot{V}O_2$ max in running (80.5 - 86.3 %) as opposed to cycling (72.3 - 78.9 %). Davis et al. (1976) showed arm cranking to elicit AT at only 46.5 ± 8.9 % $\dot{V}O_2$ max while cycling and treadmill walk - running occurred respectively at higher percentages of $\dot{V}O_2$ max (63.8 ± 9.0 & 58.6 ± 5.8 %). Withers et al. (1981) reported anaerobic threshold in runners to occur closer to $\dot{V}O_2$ max on the treadmill (77.3 ± 2.6 %) as opposed to the cycle ergometer (61.2 ± 4.9 %). Similar values were reported on the treadmill and the cycle ergometer for cyclists. Although there was no statistical difference between cyclists and runners when AT was expressed as a percentage of $\dot{V}O_2$ max, when expressed in $\dot{V}O_2$ $l * min^{-1}$ or $ml * kg^{-1} * min^{-1}$, cyclists scored significantly higher than runners when tested on a CE whereas runners scored significantly higher on a TM. These studies suggest AT to be both a function of muscle mass engaged during the exercise and the metabolic properties of the muscles. With endurance training, increased lipid oxidation in the exercising muscles has been shown to slow the rate of glycolysis (Rennie & Holloszy, 1977) and inhibit lactate formation (Rennie et al. 1976). Thus, combined with the previously mentioned local muscular adaptation occurring due to endurance training, a muscle specific mechanism for raising anaerobic threshold is evident. The findings of the present study (Table 3) support the hypothesis that VT is a function of the muscle mass engaged in exercise, however no conclusions can be made on the specificity of training effect since training was not quantified in this study.

In comparing the relationship of the physiological variables with performance in each phase of the triathlon the " quality " of performance in each phase was assessed. A valid comparison of the relationship of body composition to completion time in in the swim and cycle triathlon sections would be impossible if the population was better trained and therefore performed better in cycling opposed to swimming. This could lead to spurious relationships between these variables simply because of different training states in each exercise mode. The quality of performance in each phase of the triathlon was assessed by calculating the percentage of time spent by the fastest competitor (a criterion performance) in relation to the rest of the triathlete group (Table 1). Performance in each component of the triathlon was of equal quality since there were no significant differences in the level of group performance across triathlon phases. Comparisons of the prediction capabilities of physiological variables to performance in the different triathlon phases is therefore justified.

The mean amount of overall triathlon time accounted for by each phase of the triathlon is reported in figure 3. Completion times for all three phases were significantly related to overall triathlon time ($\underline{p} < 0.001$) and the correlations decreased in the order of run ($r = 0.93$), cycle ($r = 0.90$) and swim ($r = 0.77$). This relationship is similar to that reported by Dengel et al. (1989). These investigators reported correlations with overall time of $r = 0.97$, 0.81 and 0.30 for run, cycle and swim times respectively, in a triathlon where run time accounted for 41%, cycle time 49% and swim time 10% of total triathlon time. Further research is required to determine if the correlations in both of these studies reflect the importance of each event physiologically to overall time or are simply reflections of the ratio of time spent in each phase to overall time. In both studies, since run time accounts for the most variance in the prediction of overall time and since it takes less of total completion time than cycling time it would seem to be a combination of both these factors. That swim time is not significantly related to overall time in the study by Dengel et al. (1989) may be a reflection of the low fraction of total triathlon time; however, a significant relationship occurred in this study where swim time accounted for only 5% more of overall time than in the Dengel et al. (1989) study.

The time to complete the swim portion of the triathlon was most significantly correlated with relative swim $\dot{V}O_2$ max (r = -0.74), followed by the resistance pulled in tethered swimming at VT (r = -0.70) and the specific energy cost of swimming (r = 0.56) (Table 4). The relationship of other physiological variables with swim time were non - significant.

Many studies in the past have reported absolute $\dot{V}O_2$ max values for swimmers in the belief that body mass is supported by the bouyancy force of the water (Holmer, 1974; Astrand & Rodahl, 1977). In this study, relative TS $\dot{V}O_2$ max (r = -0.74) was a stronger predictor of swim time (ST) than absolute $\dot{V}O_2$ max (r = -0.58). This confirms other research that found expressing $\dot{V}O_2$ max as an absolute value had limitations since height, body mass, lean to fat ratio and surface area all have been found to contribute to drag, density and torque around the center of volume, which theoretically would affect swim performance (Kearney & Van Handel, 1989; Montpetit et al., 1988; Huijjing et al., 1988).

Not only was relative $\dot{V}O_2$ max a stronger predictor of ST than absolute $\dot{V}O_2$ max, it was also the strongest predictor of all the physiological variables entered against ST (Table 4). This supports the contention that $\dot{V}O_2$ max is important to endurance performance. This is in contrast to the findings of other triathlete studies that found TS $\dot{V}O_2$ max to be a non - significant predictor of swim performance (r = - 0.49, Dengel et al., 1989; r = -.50, Kohrt et al., 1987a). Both non - significant (r = -.40, Costill et al., 1985) and significant (r = -.62, p < .005, Van Handel, 1988) correlations have been reported between relative $\dot{V}O_2$ max and swim performance in competitive swimmers.

By examining factors associated with a high $\dot{V}O_2$ max the rationale behind the contention that $\dot{V}O_2$ max is important to endurance performance may be better understood A high $\dot{V}O_2$ max is associated with an increase in the efficiency of the cardiovascular system (lower heart rate and stroke volume for a given workload) (O'Toole, 1989b), an increased maximal cardiac output, increased blood volume and increases in the O_2 extraction and utilization capabilities of the peripheral muscle (Fox & Mathews, 1981; p 305). The contribution of $\dot{V}O_2$ max to endurance exercise may be to lower muscle lactate and hydrogen ion concentration (thereby attenuating pH drops) for a given exercise intensity, decrease the rate of glycogen depletion and increase fat metabolism (O'Toole, 1989b). With better O_2 extraction in the exercising muscles, the total amount of muscle blood flow necessary to supply O_2 for a given workload is decreased and more blood can be distributed to the skin for cooling (Hayward, 1981) providing a thermoregulatory advantage.

It has been suggested that endurance performance may be related to the ability to do high amounts of work at or below VT, thereby sparing muscle glycogen and avoiding a drop in muscle pH due to lactic acid formation (MacDougall, 1977). In support of this hypothesis, performance in the swim portion of the triathlon was significantly correlated to the resistance pulled at VT (r = -0.70). No comparisons can be made with other swim studies, however, since VT has not been previously reported in swimming. Power output at AT, which is a similar measure to resistance pulled at VT in swimmers, has however been shown to be an excellent predictor of performance in other endurance events such as running (Murray et al., 1987).

The specific energy cost of tethered swimming (SEC), an index of economy of movement, was also significantly related to swim performance in the triathlon (r = 0.56)(Table 4). It has been suggested that economy is more critical for success in sports with a high skill component (Kearney & Van Handel, 1989). Swimming is more technically demanding, and hence biomechanical skill is of greater importance for metabolic economy in swimming than in running or cycling (Kearney & Van Handel, 1989). The stronger relationship between swim time and the specific energy cost of activity than those found for run and cycle times lends support to this hypothesis and to the suggestion that economy is highly related to endurance swim time (Montpetit et al., 1988; Lavoie & Montpetit, 1986; Miyashita, 1978; Touissant et al., 1988; Costill et al., 1985; Van Handel et al., 1988).

When the physiological variables were examined in combination for their relationship to ST using forward regression analysis, the most significant model for the prediction of ST included body mass, relative swim $\dot{V}O_2$ max and SEC ($R^2 = 0.72$). The exclusion of SVTRES, which was significantly correlated in isolation, may be due to colinearity with SEC, since there was inter-relationship between these two variables ($r = -0.72$). Since substitution of SVTRES for SEC in the regression equation accounts for only 4 % less of the variance in predicting swim completion time, the contention that SEC and SVTRES are related is further supported. In running, the velocity at VT has been shown to be related to running economy (Kearney & Van Handel, 1989), therefore it is possible that a similar relationship may occur between SEC and SVTRES. The inclusion of body mass into the regression equation would seem to highlight the influence of body size on drag in the water (Montpetit et al., 1981). Huijjing et al. (1988) found body mass to be highly correlated with variables of active drag ($r = 0.82$ to 0.89, $p < .05$). Since increased drag increases O_2 requirements, a larger swimmer with greater drag, must do more work to achieve the same velocity as a smaller swimmer, and is therefore at a competitive disadvantage. The finding in this study that body mass was negatively correlated to SEC ($r = -0.64$) lends further support to this hypothesis. Although contributing to the most significant three variable model for the prediction of swim time, body mass was not a significant contributor alone and accounted for only 6 % of the total variance in the three variable equation. The most significant model ($R^2 = 0.66$), with significant F values for all predictors was a two component model including SEC and relative swim $\dot{V}O_2$ max (which has body mass as an integral component) (Figure 5). This model is in agreement with the theoretical equation presented by Kearney & Van Handel (1989) that expresses swimming velocity as a function of metabolic power ($\dot{V}O_2$ max) and economy as metabolic cost per unit distance (SEC). This relationship implies that any improvements in $\dot{V}O_2$ max or economy may improve performance over a given distance.

Therefore successful performance in the swim portion of the triathlon can best be predicted by a highly developed aerobic power and economy of movement in swimming. The importance of being able to perform high amounts of work without producing lactate must also be considered (RESVT). This variable may be related to the economy of swimming but is also physiologically trainable (Poole & Gaesser, 1985; Henritze et al. 1985).

Time to complete the cycling leg of the triathlon was most highly related to absolute cycle ergometer $\dot{V}O_2$ max (r = -0.72)and power output at VT (r = -0.72), followed by height (r = -0.64), body mass (r = -0.60) and absolute strength of leg flexion (r = -0.58). Relationships with other physiological variables were non - significant.

The strong correlation of absolute cycle ergometer $\dot{V}O_2$ max (CVO2MA) with cycling time (CT) supports the hypothesis that $\dot{V}O_2$ max is important to endurance performance. It is also in agreement with relationships found between cycling $\dot{V}O_2$ max and performance in other studies (r = -0.93, Foster & Daniels, 1975; r = -0.78, Kohrt et al., 1987a; r = -0.70, Dengel et al., 1989); however, weak correlations (r = -0.45) have also been reported (Krebs et al., 1986).

CT in the triathlon was also highly correlated with power output at VT on the cycle ergometer (CVTPO). This is in agreement with the finding that $\dot{V}O_2$ at lactate threshold is highly related to cycling performance (r = 0.90) (Coyle et al., 1988). Similar relationships have been reported for running velocity at AT and running performance (Murray et al. 1987; Weltman, 1989). Since the ability to produce a high power ouput at AT has been hypothesized to spare muscle glycogen and decrease lactate and H^+ formation at a given workload (MacDougall, 1977) and since endurance training has been shown to elicit increases in $\dot{V}O_2$ at AT (Poole & Gaesser, 1985; Henritze et al., 1985; Gaesser & Poole, 1986; Tanaka et al. 1984;1986) and increases in power ouput at AT (Henritze et al., 1985; Sjodin et al., 1982) it is hypothesized that as well as being a good predictor of CT, CVTPO may also be a determinant of endurance cycling performance.

Body height, mass and absolute leg flexion strength were each related to cycling performance in the triathlon, however high intercorrelations existed between these variables. It may be that these variables each reflect a common trait related to cycling. Several hypotheses are suggested.

Increased height may provide some mechanical advantage for cyclists. Carmichael et al. (1982) found that at a fixed crank length, pedalling efficiency varied with upper leg length, and that crank length on most commercially available bicycles was too long for most cyclists. Although crank length and upper leg length were not measured in this study if this relationship existed then the taller cyclists would better suit common crank lengths and thus pedal more efficiently.

Strength is known to be a function of muscle mass (Ikai & Fukanaga, 1968; Berger,1982; p23). Large athletes, associated with a large muscle mass, tend to have high absolute strength while smaller athletes have a higher strength to mass ratio (Berger,1982; p23). In cycling, since the body mass is supported, absolute strength would be of more importance. Hence, during a race, cyclists with high absolute strength values may be working at lower percentages of their absolute strength than weaker individuals. This would enhance endurance performance in the cycling leg of the triathlon due to decreasing the relative demands placed on the leg musculature and possibly sparing muscle glycogen. Hickson et al. (1988) found that increases in leg strength of 30 % increased time to fatigue (80 min) by 20 % in cycle ergometry. They hypothesized that this was due to the strength effects on fiber type recruitment. In submaximal cycling (60 rpm, 85 % $\dot{V}O_2$ max) the peak tension developed with each pedal thrust is 50 - 60 % of maximal force. With a strength increase of 30 %, peak tension would decrease from 50 - 60 % of maximal force to 35 - 45 % and therefore increase the ratio of slow twitch : fast twitch fibers recruited, and delay fatigue. That leg flexion and not leg extension strength was significantly related to cycling time may be due to muscle recruitment patterns in cycling. Hip extension is a major movement executed during pedalling

(Faria, 1984) and the muscles involved in hip extension, the gluteus maximus and part of the hamstring group, are also involved in leg flexion. As well, the gluteus maximus is active during the first 45 degrees of the power stroke in pedalling and the hamstrings are active during the last 45 degrees of the power phase (Faria, 1984). The knee extensors, utilized in leg extension, are active over a 70 degree section of crank revolution at the same time as the hamstring muscles (Faria, 1984). Although the percentage of peak force each muscle group is exposed to during cycling has not been reported, the finding that the leg flexion muscles are active for more of the crank revolution than the leg extensors may explain the stronger relationship of leg flexion ($r = -0.58$) to cycling completion time than leg extension ($r = -0.48$,).

Forward regression analysis revealed that a two variable model including height and absolute cycling $\dot{V}O_2$ max was the model with the highest multiple R ($R^2 = 0.55$) for the prediction of cycling time. Height contributed to only 3 % of the variance however, and was a non - significant contributor to the overall prediction of cycling time when combined with cycling $\dot{V}O_2$ max. Therefore, by combining the physiological variables entered against cycling time no significant prediction power was gained. C$\dot{V}$O2MA and CVTPO accounted for identical amounts of variance ($R^2 = 0.52$)

and are the best single predictors of cycling performance (Figure 5).

The quality of the bicycle used in the triathlon is also known to affect the efficiency of riding (Faria et al. 1984). This was not controlled in this study and may account for some of the variance in cycling performance that was not accounted for in the prediction equations.

The residual effects of the triathlon swim prior to the cycle must also be considered to have a possible effect on cycling performance since blood glucose decreases (Woodward et al., 1983), fluid shifts (Wells et al., 1987), dehydration (Davidson et al., 1986) and/or thermoregulatory impairment (Kreider et al. 1988)may occur. Kreider et al. (1988) found triathlon cycling work output could not be maintained at the same level as a control cycle. In this study, CT was significantly ($p < .01$) related to absolute swim $\dot{V}O_2$ max ($r = -0.68$), the economy of swimming ($r = 0.58$) and the tethered swim load pulled at VT ($r = -0.57$) which in view of other findings may support a residual affect of swimming on CT.

Running time was most strongly correlated with running velocity at VT ($r = -0.89$) followed by relative run $\dot{V}O_2$ max ($r = -0.64$), percent body fat ($r = 0.60$), absolute leg flexion strength ($r = -0.55$) and body height (r = -

0.51). The remaining physiological variables entered with run time were non - significant predictors.

The significant correlation of running velocity at VT with run time was similar to correlations in several other studies with endurance runners. Tanaka et al. (1984) found correlations of between -0.79 and -0.83 between velocity at AT and 5000 m run performance and correlations of -0.81 to -0.84 between velocity at AT and 10,000 m race performance. Similarily, Murray et al. (1987) reported a correlation of -0.80 between 8 km run time and velocity at 4.0 mM blood lactate. $\dot{V}O_2$ and velocity at VT have been shown to increase with endurance training (Poole & Gaesser,1985; Henritze et al., 1985; Gaesser & Poole, 1986; Tanaka et al., 1984, 1986; Sjodin et al., 1982) and the effect of this increase is to attenuate muscle pH decreases and fatigue as well as spare muscle glycogen (MacDougall, 1977). It is therefore hypothesized that running velocity at VT is probably more than just a predictor of RT and may be a determinant of running performance.

Both non-significant, r = -0.12 and -0.39 (Conley & Krahenbuhl, 1980; Housh et al., 1988) and significant, r = -0.53 and -0.76 (Tanaka et al., 1984; Murray et al., 1987) correlations between $\dot{V}O_2$ max and performance in running have been reported. Correlations of r = -0.55, and r = -0.78 between run $\dot{V}O_2$ max and triathlon run time have been reported by Dengel et al. (1989) and Kohrt et al. (1987a) respectively. In this study a correlation of r = -0.64 was found between $\dot{V}O_2$ max and 9 km run time in a short course triathlon. As previously stated, a high $\dot{V}O_2$ max may be advantageous for endurance performance since it increases cardiovascular efficiency and peripheral O_2 extraction and utilization capabilities. These adaptations will improve O_2 delivery to the muscle allowing a greater rate of aerobic energy production. For shorter distances, such as those experienced in a short course triathlon, $\dot{V}O_2$ max may be more important since the rate of aerobic energy production is more relevant than the capacity of the aerobic system which is of more importance in longer duration events (Thoden et al., 1982) such as an Ironman distance triathlon.

The positive relationship of body fat percentage to run time (r = 0.60) suggests that individuals with higher amounts of body fat will take longer on the run portion of the triathlon. This parallels much of the endurance literature that has suggested fat is a disadvantage to the endurance athlete since it must be carried throughout an event, contributing to increased energy requirements, but is a metabolically inert tissue (Vrijens et al. 1982)

The negative relationship of body height to running time in the triathlon (r = -0.51) suggests taller triathletes to perform better during the run. Perhaps, taller runners cover more distance per stride than shorter runners and thus are at an advantage in running.

Absolute leg flexion strength correlated negatively with run time (r = -0.55). In comparison to weaker competitors, triathletes with high absolute strength values should be able to work at a lower percentage of their absolute strength for a given submaximal intensity while running. This would reduce the demands placed on the legs throughout the run, and possibly spare muscle glycogen for use at a later stage of the race. Hickson et al. (1988) found however that 10 km run time was not significantly affected by a mean increase of 30 % in leg strength. They stated that before strength training subjects were exerting only 20 % of peak maximal force while running a 10 km time trial (mean time = 42 minutes). Any subsequent strength increases that may have decreased the percentage of peak maximal force required in running would therefore have had a small effect on changing fiber type recruitment since at 20 % of peak force fast twitch fiber recruitment is negligible. On this premise, strength training may therefore only be advantageous in running events where the percentage of peak force required recruits a substantial amount of fast-twitch fibers. Run performance in short or long course triathlons would therefore not be expected to significantly relate to leg strength. That strength may be a determinant of cycling performance has already been mentioned, thus, in triathletes with strong legs a residual fatigue effect of cycling on running may not be as evident.

Forward linear regression analysis found that %BF, the specific energy cost of running (REC) and RVTV formed the most significant model for the prediction of run time (R^2 = 0.78). However, REC and %BF did not significantly contribute to the prediction power of this model. Therefore, RVTV is the best predictor of run performance in a short course triathlon, and the addition of other physiological variables does not significantly add to the variance accounted for in the prediction of run time (Figure 5).

It is possible that residual effects of previous swimming, and cycling may have affected run performance time. That dehydration, fluid shifts, blood glucose decreases and thermoregulatory impairment occur as exercise progresses has previously been stated. Kreider et al. (1988) observed significant elevations in $\dot{V}O_2$, heart rate, arterial-venous O_2 difference and rectal temperature, and significant decreases in stroke volume and mean arterial pressure in a triathlon run compared to a control run. Mayers et al. (1986) found running time to exhaustion was decreased after prolonged cycle ergometry. These studies and the significant correlations ($p < .01$) between RT and CT ($r = 0.74$), ST ($r = 0.70$), absolute cycle $\dot{V}O_2$ max

(r = -0.71) and relative swim $\dot{V}O_2$ max (r = -0.70), suggest that previous swimming and cycling may affect run performance in the triathlon.

Overall triathlon performance was significantly correlated with $\dot{V}O_2$ max measures in swimming (-0.71), cycling (-0.76) and running (-0.57). O'Toole et al. (1987b) also found significant correlations between cycle (-0.52) and treadmill running $\dot{V}O_2$ max (-0.55) and overall finish time in a triathlon.

That $\dot{V}O_2$ max in each exercise mode was significantly correlated with overall finish time (Table 7), highlights the importance of specific aerobic power training in swimming, cycling and running. Even with a large range of correlational results between $\dot{V}O_2$ max and performance for each exercise mode, a common finding in this study and others is that high aerobic power is generally a trait of successful competitors in swimming, cycling and running. The variation in correlations may be a result of different race distances used in correlational analyses and possible differences in skill and training level within the groups studied (heterogenous vs homogenous). The role of $\dot{V}O_2$ max may be most important as a prerequisite for the development of other physiological variables that make more tangible contributions to improving endurance performance. For example, $\dot{V}O_2$ max sets the upper limit for exercise at a steady state $\dot{V}O_2$ and the $\dot{V}O_2$ at which AT can occur (Coyle et al., 1988). Therefore besides being a good predictor of endurance performance $\dot{V}O_2$ max may also be an important determinant of endurance performance in each phase and overall in a triathlon.

Significant correlations between indices of work at VT in each exercise mode and overall performance in the triathlon were found (Table 7). Again, this suggests the importance of specific training in each exercise mode. It has been hypothesized that the ability to do high amounts of work at or below VT, thereby sparing muscle glycogen and avoiding a drop in muscle pH due to lactic acid formation is important for endurance performance (Macdougall, 1977). Thus a high VT may be both a good predictor and a prerequisite to successful performance in a short course triathlon.

SEC was the only index of economy significantly related to overall performance in the triathlon (Table 7). This could mean that swimming, the first event in the triathlon, influences performance in the latter stages of the race. Perhaps uneconomical swimmers are at a disadvantage during cycling or running due to their previous swim causing premature glycogen depletion, increased hydrogen ion concentration, fluid shifts, dehydration or thermoregulatory impairment. These factors have been documented to occur in prolonged exercise such as the marathon and in sequential exercise such as the triathlon (Kreider et al. 1988; Wells et al. 1987). The findings of this study suggest that swimming economy is an important predictor and may be a significant determinant of overall triathlon performance and that in addition to training the physiological components important for endurance performance, triathletes should also work on improving stroke technique in swimming. A recent study by Touissant (1990) supports this idea since propelling efficiency in a group of well trained triathletes was 17.7 % lower than in a well trained group of competitive swimmers.

Besides being significantly correlated to overall time, height and percent body fat were significantly related to run time and have been previously discussed. Since run time had a very strong correlation with overall time (r = 0.93), the relationship of height and %BF to overall completion time may be due to this intercorrelation.

Absolute leg flexion strength was significantly related to performance in the cycle and run stages as well as the overall triathlon and was discussed previously. If leg strength did improve performance in these phases of the triathlon then overall performance may also have been affected since the cycle and run portion of the race account for over 4/5 of total performance time.

Forward linear regression analysis determined that the most significant model for the determination of overall triathlon completion time ($R^2 = 0.90$) included SEC, RVTV and absolute leg flexion strength. Leg flexion strength did not significantly add to the prediction power of the model however so it was excluded. SEC and RVTV were the best combination of variables that both significantly contributed to the prediction of overall completion time ($R^2 = 0.89$).

Since swimming accounted for only 15 % of total triathlon time, the influence of swimming economy on overall performance suggests that the residual effects of swimming prior to cycling and running may be of importance.

RVTV is highly related to work indexes at VT and $\dot{V}O_2$ max in other exercise modes (Table 7). Whether this could reflect the concurrent training practices of the triathletes or a transfer of the physiological benefits of training in one exercise mode to another is open to question. Nevertheless, RVTV seems to be especially important to overall triathlon performance. Since the run is the last event in the triathlon residual effects of prior exercise may lead to fatigue caused by muscle glycogen depletion and decreased muscle pH. This may make RVTV especially important to performance since in comparison to a competitor with a low RVTV a triathlete with a high RVTV would decrease the demands placed on already depleted muscle glycogen stores and would decrease lactate and H^+ at a given workload. In the final stages of a race this could be a critical factor.

A Summary of the Predictors of Triathlon Success

Swim Time : Relative swim $\dot{V}O_2$ max, load pulled at VT in tethered swimming and the economy of swimming were all singularly related to swim time (Table 4) The best combination of variables for the prediction of overall swim time was relative swim $\dot{V}O_2$ max and the economy of movement in swimming (Figure 5)

Cycle Time: Absolute cycle $\dot{V}O_2$ max, power output at VT, absolute leg flexion strength and height were each singularly related to cycling time (Table 5). No combination of variables significantly improved the prediction of cycling time over absolute cycle $\dot{V}O_2$ max or power output at VT. (Figure 5)

Run Time: Running velocity at VT, relative run $\dot{V}O_2$ max, body fat percentage, height and absolute leg flexion strength were each singularly related to run time (Table 6). No combination of variables significantly improved the prediction of run time over running velocity at VT (Figure 5).

Overall Time: $\dot{V}O_2$ max and work indexes at VT for each exercise mode are each significantly related to overall time highlighting the importance of specific training in each exercise mode. Height, percentage body fat, absolute leg flexion strength and swimming economy were also each significantly related to overall triathlon performance (Table 7). The specific energy cost of swimming (swimming economy) and running velocity at VT accounted for significantly more variance in combination than any one variable alone (Figure 5).

Future Research Questions

1) A training study is suggested to investigate the effects of strength training on endurance performance in a triathlon. This would help to elucidate whether or not strength training is advantageous to any of the triathlon disciplines

2) A training study that examines the extent of the physiological benefits of endurance training crossing over from one exercise mode to another in the triathlon disciplines would enable practitioners to better prescribe training.

3) Future research is recommended into the residual effects of prior exercise in one mode of exercise on performance and physiological adjustments in another using the three disciplines of the triathlon.

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Appendix A

Terminology

$\dot{V}O_2$: Volume of oxygen consumed per minute

$\dot{V}O_2$ max: Maximal oxygen consumption per minute.

$\dot{V}CO_2$: Volume of carbon-dioxide consumed per minute

AT: Anaerobic Threshold

VT: Ventilatory threshold

$\dot{V}e$: (Minute ventilation) Volume of air expired per minute

FeO_2: The percentage of O_2 in an expired volume of air.

$FeCO_2$: The percentage of CO_2 in an expired volume of air.

R: Respiratory quotient = $VCO_2 * VO_2^{-1}$

Appendix B

Informed Consent

INFORMED CONSENT FOR RESEARCH ON THE RELATIONSHIP BETWEEN SELECTED PHYSIOLOGICAL VARIABLES AND PERFORMANCE IN THE DIFFERENT DISCIPLINES OF A TRIATHLON

TESTING PROCEDURE

For the laboratatory portion of the study you will be asked to perform three maximal anaerobic threshold/aerobic power tests, one on a treadmill, one on a cycle ergometer and one in the pool using the tethered swim apparatus. Heart rate and oxygen consumption will be monitored utilizing a Sportester PE 3000 heart rate monitor and the Beckman Metabolic Cart. You will also be asked to perform a strength test for leg extension and flexion on the Cybex Isokinetic Dynamometer. Height, mass and skinfolds will also be determined.

All testing will be supervised by qualified personnel that are trained in first-aid and for testing in the pool a lifeguard will be present.

For the performance portion of the study you will be asked to compete in a short course triathlon consisting of a 1 km swim, 30 km cycle and 9.0 km run.

The triathlon and the laboratory tests will each be separated by three days to allow for optimal recovery. On these recovery days you will be asked to refrain from intense exercise, to consume at least 15 glasses of water per day and to restrict your diet to approximately 70 % carbohydrates, 20 % protein and 10 % fat.

I have read the above and agree to participate in this research project at my own risk. No coercion of any kind has been used to aquire my participation. I am nineteen years of age or older and engage in exercise of a similar level to that required in this study as part of my regular regimen. I realize that I may expect a thorough explanation and/or demonstration of any procedures and that I may terminate participation at any time in any or all procedures of my own volition. I will also be assured anonymity of all results gathered in this research.

Having voluntarily assumed participation and the risks thereof, in the project, I hereby disclaim and release the University of Victoria, it's agents, servants or employees, including all personnel involved in the research project, from any and all liability that might otherwise arise as a result of my participation as a research subject in this study.

NAME:______________________________ DATE:_____________________

ADDRESS:____

PHONE:____

SIGNATURE:____

Appendix C

Literature Review

REVIEW OF LITERATURE

The triathlon incorporates swimming, cycling and running into one race and exposes competitors to demands not regularly occurring in single sport endurance events.. Distances range from the standard short course triathlon format of a 1.5 km swim, 40 km cycle and 10 km run to the ultradistance triathlon consisting of a 3.9 km swim, 180.2 km cycle and 42.2 km run (marathon). To understand the implications of training for three disciplines simultaneously, and those factors that limit performance time, one must be aware of the demands of a triathlon, the known physiological characteristics and training practices of triathletes and the similarities and differences between triathletes and single sport endurance athletes such as swimmers, cyclists and runners. An understanding of the energy systems involved in the sport and the way in which they are taxed is necessary and valid measures of the power and capacity of the energy systems involved must be identified.

THE ENERGY SYSTEMS

Muscle contraction requires the presence of the high energy phosphagen, adenosine triphosphate (ATP) as a chemical energy source (Fox & Mathews, 1981; p 12). ATP is in very low concentrations in the muscle (8.0 mM) and decreases only a very small amount (300 umol/min) even under intense muscular work (Lehninger, 1982; p 396). The ATP level is maintained in the working muscles by three interrelated biochemical pathways (Green,1982;p 3).

1) Creatine phosphate (CP) is a high energy phosphagen similar to ATP that is stored in skeletal muscle in amounts three to four fold greater than ATP (Lehninger, 1982; p 384). This compound is capable of splitting into inorganic phosphate (Pi) and creatine (Cr) in the presence of the enzyme creatine kinase . The energy needed for the synthesis of ATP is generated from the breakdown of this compound (Fox & Mathews, 1981; p 14; Lehninger, 1982; p 384) and is limited by the amount of stored CP in the muscle (Green, 1982; p 4; Lehninger, 1982; p 384; Fox & Mathews, 1981; p 14). This phosphagen system can therefore only produce ATP for the first few seconds of intense exercise (Fox & Mathews, 1981; p 16; Green, 1982; p 4; Lehninger, 1981; p 384) and other energy systems must be used if exercise is to continue.

2) Glycolysis involves the breakdown of carbohydrate to lactic acid in order to generate ATP and has traditionally been viewed as supplying ATP when oxygen supply is unable to keep up with the demand imposed by the muscle (Hill et al., 1924; Sahlin, 1986; Hermansen, 1969). It is able to

provide energy at a high rate (approx. 50 kcal/min) however the capacity of the system is only several minutes since the lactic acid that is produced causes muscle acidosis which contributes to muscle fatigue (Fox & Mathews, 1981; p 17; Green, 1982; p 4; Lehninger, 1982; p 401; Hermansen, 1969; p 36).

3)Exercise that must continue for longer durations requires energy predominantly produced by the aerobic system. The aerobic energy system is the dominant ATP supply system used for exercise of low intensity (up to 30 kcal/min) lasting for durations of between two minutes and many hours (Howald,Von Glutz & Billeter, 1978). It involves the combustion of a fuel in the mitochondria of muscle cells in the presence of oxygen (Green, 1982; p 4). The fuel for this process can come from within the muscle, eg. free fatty acids, glycogen and lactate, and from outside the muscle (free fatty acids from adipose tissue, glucose from the liver) (Green, 1982; p 9; Brooks, 1985). Because oxygen is required this system is dependent on the ability of respiratory and cardiovascular systems to take up and deliver large amounts of oxygen to the mitochondria in the working muscles (Green, 1982; p 9).

These three energy systems do not act independently but overlap contributing different portions of the energy required for work as the exercise intensity and duration changes. For the endurance athlete it is desirable to work for long durations at as high an intensity as possible. This is limited by the rate at which an athlete can utilize oxygen and the intensity at which they can work without shifting from the aerobic system to the lactate system, where fatigue will occur rapidly due to glycogen depletion (O'Toole et al., 1985) and lactic acid formation causing a decrease in pH.

MAXIMAL OXYGEN CONSUMPTION

Maximal oxygen consumption ($\dot{V}O_2$ max) is a measure of the rate at which energy can be released exclusively from oxidative processes (aerobic power) and is dependent upon peripheral and central factors. The peripheral component is the ability of the muscles to take up and utilize oxygen in breaking down fuels and the central component is the combined ability of the pulmonary, cardiovascular and cellular mechanisms to transport oxygen to the muscle (Thoden et al., 1983; p 39).

THE SPECIFICITY OF VO_2 MAX

The specificity of $\dot{V}O_2$ max is well understood. Gleser et al. (1974) found that $\dot{V}O_2$ max was 10 % higher when arm work was added to leg work on a cycle ergometer and speculated that $\dot{V}O_2$ max was a function of the mass of muscle engaged in the exercise. Supporting this hypothesis, Secher et al. (1974) reported combined arm-leg ergometry to elicit higher $\dot{V}O_2$ max values than leg ergometry alone, with the difference being most evident in arm trained subjects. The better performance of the arm trained subjects suggests local muscular adaptation as being an important factor in $\dot{V}O_2$ max assessment.

Pechar et al. (1974) and Roberts and Alspaugh (1972) found treadmill training to produce similar $\dot{V}O_2$ max increases regardless of whether $\dot{V}O_2$ max was assessed on the treadmill or cycle ergometer. Bicycle training however, produced greater improvements when tested on the bike than while tested running. They speculated that the more specific training effects of cycling were due to muscle isolation causing changes locally at the muscle level such as increased vascularization (Roberts & Alspaugh, 1974) and enhanced aerobic enzyme activities (Stromme et al., 1977). Consistent with these findings Magel et al. (1975) found that swim training for $\dot{V}O_2$ max in male recreational swimmers led to significant $\dot{V}O_2$ max improvement when assessed by tethered swim (11 %) however little improvement when assessed on the treadmill. These studies indicate that aerobic adaptation and the assessment of $\dot{V}O_2$ max are dependent upon the mode of exercise.

Treadmill $\dot{V}O_2$ max tests elicit higher values than cycling and swimming tests with cycling tests being 5-8%

lower (Faria, 1984; Saltin & Astrand, 1967; Burke, 1980)and swim tests being 15-16% lower (Holmer, 1974; Magel, 1974). The state of training however, may account for variations in aerobic power when comparisons are made between $\dot{V}O_2$ max measured during different forms of work. Elite athletes trained in one type of movement reach higher levels of maximum oxygen uptake when tested in that mode of exercise. This has been demonstrated in cyclists (Stromme et al., 1977; Verstappen et al., 1982; Withers et al., 1981; Hagberg et al., 1978), swimmers (Magel & Faulkner, 1967; Dixon & Faulkner, 1971; Holmer, 1972) as well as x-country skiers and rowers (Holmer, 1972). Since triathletes train by swimming, cycling and running it is desirable to test their $\dot{V}O_2$ max values in each of these exercise modes. A number of testing options are available so it is therefore necessary to review the most valid, reliable and practical of the methods for imposing sport specific loads.

ERGOMETRY FOR $\dot{V}O_2$ max TESTING

The motorized treadmill is generally accepted as being the optimal method for imposing run workloads on athletes. Both velocity and elevation are controllable, it requires little skill and requires the activation of a large amount of an athletes muscle mass; however,for athletes trained in other exercise modes it may not be the most suitable ergometer.

CYCLING ERGOMETRY

Trained cyclists have been shown to exceed their treadmill $\dot{V}O_2$ max values when tested using bicycle exercise (Stromme et al., 1977; Verstappen et al., 1982; Withers et al., 1981; Hagberg et al., 1978). Various methods have been used to apply cycling specific loads including riding a bike on a motorized treadmill, riding in a velodrome and riding a cycle ergometer (Ricci & Leger, 1983; Hagberg et al., 1978). Hagberg et al. (1978) found that trained cyclists exhibited similar $\dot{V}O_2$ max values when tested on a treadmill, cycle ergometer and when riding a bike on the treadmill while Ricci and Leger (1983) found that bicycle ergometry elicited a higher $\dot{V}O_2$ max than velodrome and treadmill cycling tests.

A number of studies have suggested that for cyclists an rpm of between 80 and 90 is optimal for eliciting high $\dot{V}O_2$ max values (Lavoie et al., 1978; Hagberg et al., 1978) since cyclists train close to this rpm and possible blood flow and fiber recruitment advantages may be present when compared to stationary cycling at low rpm (50-60) and higher resistance. Based on the findings of the above studies, it appears that a cycle ergometry test at speeds of 80 - 90 rpm may be optimal for the testing of $\dot{V}O_2$ max in cycle trained athletes

SWIM ERGOMETRY

In swim trained athletes, $\dot{V}O_2$ max has been determined with tethered swimming, flume swimming, free swimming and dry-land methods such as arm-cranking and swim bench ergometry (Bonen et al., 1980).

Dry-land testing using arm-crank ergometry and swim-bench ergometry has been used in an attempt to simulate the swimming movement for $\dot{V}O_2$ max testing. These methods have not proven useful however, since the movements, motor-unit activation and muscle mass engaged do not adequately mimic swimming (Bonen et al., 1980; Meerloo, unpublished masters thesis).

Swim loads may also be imposed using a swim flume. This apparatus circulates the water in a specially arranged pool so that the swimmer can swim on the spot at various speeds (Astrand & Englesson, 1972). Although this apparatus has proven to be useful in studying metabolic responses in swimming (Lavoie & Montpetit, 1986) its usefulness is limited by its accessibility.

Tethered swim is probably the most commonly used apparatus to impose swim loads. It allows the swimmer to swim in the water without any forward movement and instruments for the collection of physiological data are therefore easily attached. The body position and hydrodynamics are different from free swimming (Holmer et al., 1974) and the drag forces of the upper arm have been shown to be double those produced in free swimming (Jensen & Tihanyi, 1978). Despite these differences $\dot{V}O_2$ max values measured in tethered swimming show high correlations with flume and free swimming ($r = 0.99$) (Bonen et al. 1980).

THE RELATIONSHIP OF $\dot{V}O_2$ max TO ENDURANCE PERFORMANCE

$\dot{V}O_2$ max has been used extensively as a performance criterion for endurance athletes (Rusko et al., 1978); however, the prediction of performance from $\dot{V}O_2$ max has been investigated by a number of researchers (Hagberg et al. 1979; Foster & Daniels, 1975; Vrijens et al. 1982; Burke, 1980; Faria, 1984; Wilmore & Brown, 1974) with conflicting results. Several researchers found no significant relationship between endurance performance and $\dot{V}O_2$ max (Vrijens et al., 1982; Hagberg et al., 1979) while others found $\dot{V}O_2$ max to be a relatively good predictor of performance especially when used in conjunction with other information such as body composition, muscle fiber type, muscular strength and endurance, efficiency and biomechanics (Foster & Daniels, 1975; Burke, 1980; Faria, 1984; Wilmore & Brown, 1974). High heterogeneity of $\dot{V}O_2$ max values within a group increases the relationship of $\dot{V}O_2$ max to quality of performance (Dengel et al., 1989; Conley & Krahenbuhl, 1980; Housh et al., 1988; Coyle et al., 1988). Thus it appears that although a high $\dot{V}O_2$ max may be important it is only one of a multitude of factors affecting performance.

In order to examine reasons for the relationship of $\dot{V}O_2$ max to endurance performance it is necessary to look at changes associated with improvements in $\dot{V}O_2$ max. Endurance training leads to an increase in plasma volume (which increases stroke volume) as well as decreased catacholamines which decrease heart rate at any standard submaximal workload (O'Toole et al., 1988). These catecholamines also inhibit vasoconstriction and therefore decrease vascular resistance to blood flow. Both plasma volume increases and catecholamine decreases act to maintain submaximal and increase maximal cardiac output (O'Toole et al., 1988). At maximal loads more O_2 can therefore be supplied to the working muscles which will increase the ability to do high amounts of aerobic work. Endurance training also leads to peripheral adaptations such as increased muscle myoglobin (O'Toole, 1988; Fox & Mathews, 1981; p 294) increased size, number and membrane surface area of skeletal muscle mitochondria (O'Toole,1988; Fox & Mathews, 1981; p 295), increased activity and concentration of mitochondrial enzymes (O'Toole, 1988; Fox & Mathews, 1981; p 295) and increased capillarization of skeletal muscle (Fox & Mathews, 1981; p 305). All of these adaptations enhance O_2 extraction and utilization at the local muscle level and thereby enhance $\dot{V}O_2$ max. They also reduce the total amount of muscle blood flow necessary to supply O_2 for a given workload and thus more blood can be distributed to the skin for cooling (Hayward, 1981). These factors also help to lower blood and muscle lactate concentrations for a given exercise intensity, decrease the rate of glycogen depletion and increase fat metabolism (O'Toole, 1988). Thus these adaptations seem to link $\dot{V}O_2$ max to endurance performance.

ANAEROBIC THRESHOLD

In 1971, Costill et al. reported no significant relationship between $\dot{V}O_2$ max and marathon running success although it was evident that all runners had $\dot{V}O_2$ max values well above average. They concluded that running economy and the ability to work at a large fraction of $\dot{V}O_2$ max during the marathon competition were critical factors in determining marathon success. This ability to sustain exercise at a high percentage of $\dot{V}O_2$ max has been identified as being equal in importance to the actual $\dot{V}O_2$ max in long duration endurance events (Macdougall, 1977; p41). The highest exercise intensity that can be sustained for prolonged periods has been termed the anaerobic threshold (AT) since Wasserman & McIlroy (1964) theorized that this power output marked the transition from aerobic energy supply to anaerobiosis. These investigators observed that as exercise intensity increases lactate accumulation will be a linear function of the power output and $\dot{V}O_2$ while simultaneously the rate of pulmonary minute ventilation ($\dot{V}e$) will increase linearly with increments in work rate. Eventually a power output will be encountered at which both blood lactate and $\dot{V}e$ will increase non-linearly. This power output (AT) is termed the lactate threshold (LT) or ventilatory threshold (VT) depending upon which physiological indice is considered (Brooks,1986). Wasserman considered LT and VT to be manifestations of anaerobiosis in the muscle (Wasserman & Mcilroy, 1964) and to be separate effects of the same stimulus (Wasserman et al., 1973). This has proven to be false however since Neary et al. (1985),using a one legged training model and glycogen depletion, found that LT and VT were coincidental and not cause and effect since with glycogen depletion LT was lowered but VT remained at the same percentage of $\dot{V}O_2$ max.

THE SPECIFICITY OF THE ANAEROBIC THRESHOLD

The specificity of movement is important when assessing anaerobic threshold. Withers et al. (1981) investigated the difference between cyclists and runners and found that when AT was expressed in $\dot{V}O_2$ $l * min^{-1}$ and $\dot{V}O_2$ $ml * kg^{-1} *$

min^{-1} that cyclists scored significantly better than runners when tested on a cycle ergometer whereas runners scored significantly better when tested on a treadmill. Similarily, Brouha (1945) reported a specificity of blood lactate response during running and rowing. AT has been shown to occur at a significantly greater percentage (5-12%) of $\dot{V}O_2$ max on the treadmill than the bicycle ergometer (Withers et al., 1981; Wiswell et al., 1979) while Davis et al. (1976) showed AT to occur at 46.5% $\dot{V}O_2$ max for arm cranking, 66.3 % for cycle ergometry and 74.3 % for treadmill running. The literature therefore suggests AT to be a function of the muscle mass involved combined with local muscle metabolic properties.

THE DETERMINATION OF THE ANAEROBIC THRESHOLD

A non-linear increase in either minute ventilation or blood lactate concentration when plotted against $\dot{V}O_2$ ($\dot{V}e/\dot{V}O_2$ & $La/\dot{V}O_2$ respectively) is commonly used for the determination of AT. Other gas exchange measures including a non-linear increase in minute ventilation, non-linear increases in CO_2 output and abrupt systematic increases in the respiratory exchange ratio have also been used to detect AT (Caizzo et al., 1982). $\dot{V}e/\dot{V}O_2$ has been shown however to provide the highest correlation ($r = 0.93$) with the lactate threshold and has proven to be the most reliable of the gas exchange estimation methods ($r = 0.93$) for test/re-test situations (Caizzo et al., 1982).

The detection of a departure from linearity has been estimated both subjectively by visual estimation (Davis et al., 1976; Wasserman et al.,1973) and objectively by use of multiple linear regression (Orr et al., 1982; Neary et al., 1985; Neary & Wenger, 1986). Orr et al. (1982) found reliability coefficients for several "expert" observers to be 0.81 and 0.87 while using a computer algorithm and multiple linear regression it was found to be 1.0 and was therefore deemed more reliable.

RELATIONSHIP OF ANAEROBIC THRESHOLD TO ENDURANCE PERFORMANCE

Exercise at an intensity above AT reduces endurance time because of such factors as decreased muscle pH and a reduced ability to mobilize lipids and therefore spare muscle glycogen (MacDougall, 1977). Muscle glycogen depletion becomes a limiting factor only in the marathon type events and is not of relevance in events shorter than thirty minutes (Thoden et al. 1983; p41). In support of this Coyle et al. (1988) found $\dot{V}O_2$ at LT to be highly related to cycling performance and the velocity at AT has also been highly related to running performance (Tanaka et al., 1984; Murray et al., 1987), thus AT seems to be a strong predictor of endurance performance.

Economy of Movement

Economy has been defined as the metabolic cost , $\dot{V}O_2$, in ml * kg^{-1} * min^{-1}, of performing an activity at a standard, pre-determined submaximal intensity (Kearney & Van Handel, 1989). A variation of this is to calculate the specific energy cost of transport, which expresses metabolic cost relative to distance (eg. ml * kg^{-1} * m^{-1}) (Kearney & Van Handel, 1989). A more economic endurance athlete uses less energy than his less economic counterpart at a standard power output and is therefore able to a) move faster or b) conserve energy for the later stages of an endurance event.

Economy may be influenced by a number of factors including age, training, genetics, gender, body mass, skill and specialization and may be more critical for success in sports with a high skill component such as swimming (Kearney & Van Handel, 1989). Indices of economy have been related to performance in swimming (Montpetit et al., 1988; Lavoie & Montpetit, 1986; Miyashita, 1978; Touissant et al., 1988; Costill et al., 1985; Van Handel et al., 1988), cycling (Coyle et al., 1988) and running (Daniels, 1974; Sjodin & Schele, 1980; Costill et al., 1971; Housh et al., 1988), therefore economy of movement may also be of importance in a triathlon, which is a composite of all three of these sports.

STRENGTH

Strength may be defined as the peak force or torque developed during a maximal voluntary contraction (MVC) and is measured using newtons (N) or newton meters (Nm) for force and torque respectively (Sale & Norman,1983). Strength is affected by a number of characteristics including muscle and body size, muscle fiber composition, neural adaptation, age and sex.

Ikai and Fukanaga (1968) reported a positive correlation between muscle cross-sectional area and absolute strength while Berger (1982, p.23) reported a positive correlation between body mass and absolute strength and a negative correlation between body mass and the strength to mass ratio. Therefore, large athletes (associated with a large muscle size) tend to have a high absolute strength while small athletes tend to have a high strength to mass ratio.

In humans, a positive correlation has been shown between the percentage of fast-twitch (FT) muscle fibers and isometric strength (Tesch & Karlsson, 1978) and the correlation between percentage of FT fibers and strength becomes stronger as strength is measured at higher velocities (Coyle et al. 1979).

The ability of the nervous system to activate the muscle mass has been related to voluntary strength performance since motor unit synchronization has been shown to be enhanced in weight lifters (Milner-Brown et al. 1975) and in elite sprinters (Upton & Radford, 1975). Moritani and deVries (1979) found that even in simple movements the initial increases in voluntary strength were a result of neural rather than muscular adaptation.

Absolute peak strength occurs in the mid-twenties and declines gradually; at 65 years old about 80 % of peak strength is still retained (Fisher & Birren, 1947). The gender difference in strength has been suggested to be a function of muscle mass since, when strength is expressed per kg of lean body mass, this difference is reduced (Anderson et al., 1979) and when strength is expressed per unit of muscle cross-sectional area males and females are not significantly different (Ikai & Fukanaga, 1968).

Males have been shown to be able to generate a given percentage of peak isometric force more rapidly than females (Komi & Karlsson, 1979) and the male/female strength ratio has been shown to be larger at high velocities (Anderson et al. 1979). Thus, a neural mechanism (Komi & Karlsson, 1978) or a gender difference in muscle elasticity (Sale &

Norman,1983) may be partly responsible for the gender differences in strength.

THE SPECIFICITY OF STRENGTH

Specificity in strength training can be discussed under four headings: 1) movement pattern 2) velocity 3) force of contraction and 4) type of contraction (Sale & Macdougall, 1981).

MOVEMENT PATTERN - That strength improvements are specific to the exact movements used in training has been well documented (Rasch & Morehouse, 1957; Macdougall et al., 1977,79,1980a). Isometric training studies have even shown strength improvements to be specific to the joint angle trained (Lindhe, 1979). It has been suggested that a major contributor to increased strength performance is skill aquisition (Rasch & Morehouse, 1957) and that this applies equally to simple and complex movements (Sale & Macdougall, 1981).

VELOCITY - Isokinetic training studies have demonstrated a velocity specific training effect. Low velocity training increases low velocity strength with little effect on high velocity strength while similarly high velocity training improves strength at high velocity with little effect on slow velocity strength. Mixed high and low velocity training produced intermediate results (Moffroid & Whipple, 1970; Coyle & Feiring, 1980; Caiozzo et al., 1980).

Two possible mechanisms were hypothesized by Sale and MacDougall (1981) to account for the velocity specific effect: 1) velocity specific adaptation within the muscle; 2) velocity specific adaptation within the nervous system. These investigators felt that neural adaptation was primarily responsible for the velocity specific effects based on Desmedt and Godauxs evidence (1979) that the brain organizes and initiates fast ballistic movements differently than slow movements. Councilman (1976a,b) hypothesized that selective motor unit recruitment (fast or slow twitch) was responsible for the velocity effects. He theorized that strength training at low velocities recruited mainly slow twitch motor units and therefore adaptation was specific to these motor units. Similarly, training at high velocities recruited fast twitch motor units with selective adaptation to these units. In contrast is the data of Macdougall et al. (1980a) that showed hypertrophy of fast and slow twitch fibers with slow velocity weight training; Furthermore, regardless of the speed of contraction motor unit activation has been shown by electromyography to be similar provided the degree of voluntary effort is maximal (Desmedt & Godaux, 1979; Maton, 1980). FT motor units have also been shown to be activated during isometric contractions (Golhnick et al. 1974; Warmolts & Eugel,1972). Thus there seems to be no basis for the theory of selective recruitment of motor units during strength training and the specificity of velocity in strength training appears to be more related to neural factors.

FORCE OF CONTRACTION - The force of a contraction generated in strength training may dictate the energy system that is being trained. It is possible to train with a weight that only allows a single maximal lift, referred to as a one repetition maximum (1 RM), or a weight that allows a series of repetitions, for example 8-10 repetitions (8-10 RM) (Sale & Macdougall, 1981). Depending upon the scheme of training, different biochemical adaptations within the muscle may occur. Macdougall et al. (1977) observed that training with an 8-10 RM scheme causes adaptations within both the ATP-CP system and lactic acid systems. It follows that the nature of 1-3 RM training probably primarily stimulates the alactic system (Sale & Macdougall, 1981); however, research in this area has not been conclusive since similar training benefits have been reported for a wide variety of repetitions, especially beyond the 10 RM. Evidence is leaning towards no specificity effect for force of contraction (Clarke & Stull, 1970; Delateur et al., 1968; Stull & Clarke 1970; Berger, 1962a, 1963).

TYPE OF CONTRACTION - There are three types of muscle contraction: 1) Concentric - develops tension while the muscle shortens; 2) Eccentric - develops tension while the muscle lengthens and 3) Isometric - develops tension with no visible muscle shortening (Fox & Mathews, 1981; p 139-145). Eccentric contraction generates the most tension followed by isometric and isotonic (Sale & Macdougall,1981). These same investigators concluded that specificity in contraction type was a factor in strength training and was controlled by the nervous system. They hypothesized that emphasizing the same contraction type in training as occurs in performance will allow the appropriate neural adaptation to occur.

Fahey & Brown (1973) found little transfer of strength from isotonic training to isokinetic (concentric) strength. Similarly, Lindh (1979) found no transfer from isometric training to isokinetic (concentric) strength and no strength transfer from isokinetic (concentric) training to isometric strength was found by Kanehisa & Miyashita (1983).

Transfer of training effects from one contraction type to another have been reported however, by a number of other investigators. Isotonic (concentric) training was shown to improve concentric and eccentric strength but not isometric strength (Komi & Buskirk, 1972). However, isometric strength was shown to improve equally with concentric isotonic, eccentric isotonic and isometric training by Pavonne & Moffat (1985). Knapik et al. (1983) also showed isometric training to improve isokinetic concentric strength and vice-versa. Peterson et al. (in press) found isokinetic concentric training to improve both concentric and eccentric isokinetic strength. Thus, the data available in the literature is equivocal with regards to the specificity of contraction type.

STRENGTH AND ENDURANCE PERFORMANCE

Edington and Edgerton (1976, p 276) theorized that a high level of strength will enhance short term, high intensity "endurance" because a given power output can be maintained longer when it represents a relatively smaller percentage of the maximum force or power capability. This argument is the most valid when the absolute load taxes a high percentage of maximum strength and power since large variations in strength do not cause large variations in the percentage of maximal strength which is taxed during low intensity work. For example, sustaining a force of 100 N would tax 10% of the strength of a man that had a peak strength of 1000 N and 5 % of the strength of a man with a peak strength of 2000 N. If an absolute load of 800 N was used then there would be a 40 % difference in relative load (80 % vs 40 %) between the athletes instead of a mere 5 %

(5 % vs 10 %) difference. Although little research has been reported in the area some investigators have suggested that strength training may impair endurance performance at low intensities because of the following adaptations; 1) an increase in muscle and body mass that would increase the energy requirement of activities involving support of the body (Sale & Norman, 1983); 2) a decrease in mitochondrial volume density which may decrease the oxidative capacity of the muscle (Macdougall et al., 1979); 3) greater hypertrophy of fast than slow twitch muscle fibers causing greater fatigability (Thorstensson et al. 1976; Macdougall et al., 1980). These deleterious effects however, may be attenuated with concurrent aerobic and strength training (Sale & Norman, 1983; p 12). Hickson et al., 1988 found this to be the case since when leg strength training was added to a pre-existing aerobic training program, a mean increase in leg strength of 30 % was seen without changes in body composition, thigh girth or fiber composition. Citrate synthase activity and $\dot{V}O_2$ max also remained unchanged however significant increases in time to fatigue for short term endurance exercise (5 - 8 minutes) on the bike (11 %) and treadmill (13 %) and long term endurance exercise (80 minutes) on the bike (20 %) were observed. These investigators hypothesized that the improvement of endurance performance was due to an increase in slow twitch fiber recruitment since after strength training, workloads would stress the legs at a lower percentage of peak force than before.

CHARACTERISTICS OF ENDURANCE ATHLETES

The specificity principle has been demonstrated through a number of studies and experiments with examples given previously. By analysing different sports this principle can be illustrated in another way. For example, the physiology of elite endurance athletes has been well investigated (Saltin & Astrand, 1967; Rusko et al. 1978; Pannier et al, 1980; Ricci et al. 1983; Withers et al. 1981) resulting in an abundance of physiological data describing endurance runners, cyclists and swimmers. The different demands of these endurance activities are reflected by different physical and physiological characteristics reported for these athletes in their respective disciplines.

Endurance athletes tend to be light in mass and low in percentage of body fat. Mass ranging from 63.1 to 71.5 kg (Saltin & Astrand, 1967; Pannier et al., 1980; Daniels, 1974; Pollock et al., 1977; Daniels et al., 1977; Housh et al., 1988; Sjodin & Schele, 1980; Withers et al., 1981; Martin et al., 1986) and body fat percentages from 4.7 to 12.3 (Martin et al., 1986; Pannier et al., 1980; Daniels, 1974; Housh et al., 1988; Wimore & Brown, 1974; Wilmore et al., 1977; Pollock et al., 1977) have been reported for elite male endurance runners. Mean body mass values of 51.6 - 57.2 kg and mean body fat percentages of 15.2 - 18.8 have been reported for female endurance runners (Wilmore & Brown, 1974; Wilmore et al., 1977; Daniels et al., 1977; Mayhew et al., 1983). Male cyclists tend to be heavier than their running counterparts (65.7 - 72.8 kg) but of similar body composition (7.1 - 11.6 % fat) (Burke et al., 1977; Vrijens et al., 1982; Foster & Daniels, 1975; Hagberg et al., 1979; Foley et al., 1989; Lopategui et al., 1986; Withers et al., 1981; Krebs et al., 1986) while values for female cyclists closely resemble female runners (55.0 - 61.3 kg and 15.4 % body fat) (Burke et al., 1977; Burke, 1980). Male swimmers tend to weigh similar to cyclists (73.7 - 78.2 kg) and be of similar body composition to cyclists and runners (55-10 %) (Lavoie & Montpetit, 1986; Dixon & Faulkner, 1971; Di Prampero et al., 1974; Telford et al., 1988). Female swimmers are fatter (17.1 - 21.1 %) than female runners and cyclists and weigh more (60.9 - 65.8 kg) (Lavoie & Montpetit, 1986; Holmer, 1974; Wilmore et al., 1977; Mayhew et al., 1983). Since both swimming and cycling are mass supported activities extra mass may be of advantage to these athletes if it is in the form of muscle since it will increase their maximum power output potential, whereas in running where mass must be supported it will only serve to increase the workload of the athlete for any given velocity. In swimming extra fat may increase bouyancy enough to provide an advantage by reducing drag.

$\dot{V}O_2$ max values for elite male distance runners have been reported to average between 64.7 - 79.3 ml * kg^{-1} * min^{-1} (Saltin & Astrand, 1967; Daniels, 1974; Pannier et al., 1980; Hughson, 1984; Martin et al., 1986; Daniels et al., 1977; Wilmore and Brown., 1974; Tokmakidis et al., 1987; Thibault et al., 1985; Withers et al., 1981; Sjodin & Schele, 1986; Brettoni et al., 1989; Conley & Krahenbuhl, 1980; Housh et al., 1988) while values for females have been reported to average 59.1 - 62.9 ml * kg^{-1} * min^{-1} (Plowman, 1979; p 352; Daniels et al., 1977; Wilmore & Brown, 1974; Riley Hagan et al., 1987). Male cyclists average lower than male runners scoring between 61.7 and 74.0 ml * kg^{-1} min^{-1} (Saltin & Astrand, 1967; Stromme et al., 1977; Burke, 1980; Burke et al., 1977; Vrijens et al., 1982; Foster & Daniels, 1975; Hagberg et al.,1978; 1979; Brettoni et al., 1989; Coyle et al., 1988; Lopategui et al., 1986; Withers et al., 1981; Krebs et al., 1986) and female cyclists average lower than female runners with $\dot{V}O_2$ max scores averaging 51.2 - 61.3 ml * kg^{-1} * min^{-1} (Burke, 1977; 1980; Hagberg et al., 1979). Saltin and Astrand (1967) reported a mean value of 67 ml * kg $^{-1}$ * min^{-1} for elite male and a mean value of 58 ml * kg^{-1} * min^{-1} for elite female swimmers however $\dot{V}O_2$ max was assessed on cycle ergometer and not while swimming while Van Handel (1988) reported similar scores for swimmers using a free swim protocol (males = 68.2, females = 56.8 ml * kg^{-1} * min^{-1}). Holmer (1974) assessed swim and run $\dot{V}O_2$ max in a group of swimmers. For the elite group an average value of 52.1 ml * kg^{-1} * min^{-1} was found in the swim flume however a 16 % increase was observed (mean = 61.2 ml * kg^{-1} * min^{-1}) when a treadmill protocol was used. The lower $\dot{V}O_2$ max values found in swimming versus running were also found by Magel et al. (1974) for male college recreational swimmers (15 % lower). In contrast to these findings some research suggests that world class and Olympic swimmers are able to equal or exceed their running or cycling $\dot{V}O_2$ max values during swimming (Holmer, 1972; Magel & Faulkner, 1967) and trained cyclists have been reported to reach higher levels of maximal oxygen consumption (by 5.3 %) on the cycle ergometer versus the treadmill. As stated before the specificity principle must be considered when comparing any physiological testing results since the similarity of the training mode to the mode of testing will affect the score.

Skeletal muscle is an extremely heterogeneous tissue made up of several different fiber types that can combine in different proportions to give individual muscles the ability to meet various functional demands. The overall properties of a muscle depend primarily on fiber composition (Pette & Spamer, 1986). In humans, fibers that predominantly function aerobically are called Type 1 or slow oxidative (ST) fibers while fibers that function anaerobically are called Type 2 fibers (Fox & Mathews, 1981; p96). Type 2 fibers can further be broken down into type 2a (fast-oxidative-glycolytic) and type 2b (fast-glycolytic) fibers (Fox, 1984; p 317). Type 1 fibers are fatigue resistant and best suited for endurance type activities while type 2b fibers fatigue quickly and are more suited for generating high amounts of force and power. The 2a fibers combine properties of both Type 1 and 2a fibers (Fox, 1986; p 316).

It has been reported that elite endurance athletes tend to have a high percentage of slow twitch fibers when compared to the average population whereas non-endurance athletes have greater percentages of fast twitch fibers (Fox & Mathews, 1981; p 98). A positive correlation has also been demonstrated between $\dot{V}O_2$ max and the distribution of slow-twitch fibers (Bergh et al., 1978; Fox & Mathews, 1981; p 98). In specific endurance sports the predominance of one fiber type does not appear to be as evident. Long distance runners have been reported to have between 50 to 98% slow-twitch fibers (Fox & Mathews, 1981, p 97; Bergh et al., 1978) while cyclists range from 45 to 75% ST (Fox & Mathews, 1981; p 97; Burke et al., 1977; Bergh et al., 1978) and swimmers from 40 to 85% (Fox & Mathews, 1981: p 97; Bergh et al., 1978; Lavoie & Montpetit, 1986). These studies do not differentiate between Type 2a and 2b fibers.

Demands and Training Practices.

In contrast to the cyclist, swimmer or runner who is an endurance specialist that concentrates on one sport is the endurance athlete who trains to be the best at a combination of all three specialties - the triathlete. The triathlon exposes competitors to demands similar to those experienced in other endurance events (eg. marathon), as well as some not normally experienced by single sport endurance athletes. Dehydration and vascular fluid shifts are known to accompany single bouts of endurance exercise (Costill, 1986; p73; Rogers & Jooste, 1980; Senay & Pivarnick, 1985) as well as sequential exercise, such as that experienced in a triathlon (Wells et al., 1987).

Dehydration from endurance exercise occurs primarily as a result of heat production. As exercise progresses the exercising muscles produce heat (Costill, 1986; p 51). Consequently, the muscle heat raises the temperature of the blood and the body core. In order to balance heat production with heat loss, and maintain homeostasis, a portion of the blood is shunted to the cutaneous blood vessels of the skin. Here the process of sweating allows the loss of heat through evaporation. The extent of dehydration depends upon rehydration strategies and the amount of sweat that evaporates, which in turn depends upon a number of factors including exercise intensity, body size, environmental temperature, state of acclimatization, aerobic fitness and core temperature (Costill, 1986; p73).

Body water content as reflected by weight loss has been found to decrease as much as 13 to 14 percent in a marathon despite ad libitum fluid replacement (Costill,1986; p 73). The dehydration response to sequential cycling (40 km) and running (10 km), showed no order effect (3.7 % weight loss for run-bike vs 3.4% for bike run order) but found weight loss to be more severe after running (mean = 1.55 %) than cycling (mean = 0.95 %) (Wells et al., 1987). Kreider et al. (1988) found that when compared to a control cycle, body mass was not significantly different in a triathlon cycling session; however, when compared to a control run, body weight was lower ($\underline{p} < .001$) after a triathlon run. Overall triathlon weight loss was 3 %, with 1.5 % weight loss occurring during the triathlon run alone. In this study subjects drank more water during the triathlon than during the control sessions. If water consumption was standardized even greater dehydration would have been expected.

An effect of dehydration is to decrease plasma volume and therefore decrease total blood volume. A reduced blood volume reduces mean arterial pressure resulting in decreased ventricular pressure and stroke volume. If cardiac ouput is to be maintained then heart rate must increase (Kreider et al., 1988). The decreased blood volume also reduces the absolute amount of blood available to be distributed to the skin for cooling and to the exercising muscles for oxygen supply and waste removal; therefore, both endurance performance and thermoregulatory ability can be impaired. The vasodilation of peripheral blood vessels as a result of core temperature increase has a similar effect on the circulatory system (Nose et al., 1988). It can therefore be difficult to differentiate between the influences of dehydration and thermoregulation on the circulatory system, especially since they usually act together.

Besides the dehydration effects there are also fluid shifts within the body that affect plasma volume and can be potentially deleterious. These shifts of plasma from the vascular space to the interstitium, and vice-versa, occur due to many factors including dehydration itself (Nose et al., 1988), body position (Pivarnick et al., 1986), water immersion (Hinghofer-Szalkay et al., 1987), menstrual phase (Stephenson & Kolka, 1988), and exercise (Stephenson & Kolka, 1988; Sawka et al., 1985; Brandenberger et al., 1986; Pivarnick et al., 1988). Changes during exercise are mainly due to changes in capillary hydrostatic pressure and intramuscular osmotic pressure (Pivarnick et al., 1988).

Fluid shifts during ergometer cycling and treadmill running have been investigated. Ergometer cycling leads to plasma volume reduction, with a significant correlation between hemoconcentration and exercise intensity (Senay, Rogers and Jooste, 1980; Senay and Pivarnick, 1985). Treadmill exercise effects on plasma volume dynamics are more confusing since some investigators report plasma volume expansion (Kolka et al., 1982; Pivarnick et al., 1984; Sawka et al., 1984) while others report a decrease (Costill and Fink, 1974; Maron et al, 1975; Sawka et al., 1984; Wells et al., 1982) or no change (Rocker et al., 1976). Only one study reported fluid shifts with sequential exercise. Wells et al. (1987) found significant hemoconcentration (-6 to -8 % blood volume; -8 to -10 % plasma volume) with moderate dehydration (-3 to -4 % body mass) despite ad libitum fluid replacement with successive running and bicycling performance. They found more severe fluid compartment shifts occurred on the initial phase regardless of exercise mode (-6.8 % for run and -9.9 % for cycle). Blood and plasma volume changes during the second mode of exercise were of minor extent with the major difference occurring in red cell volume. When fluid shifts were calculated on a per hour basis, shifts were greater during running than during cycling. These investigators failed to control for posture effects however so it is not possible to quantify the amount of fluid that shifted due to exercise alone.

In triathlons over 4 hours, hyponatraemia, an electrolyte disturbance characterized by serum sodium values less than 135 mEq * L $^{-1}$, has been reported to occur in conjunction with dehydration (Hiller, 1989). It occurs as a result of massive unreplaced sodium losses via sweating, in combination with partially replaced massive water losses. Manifestation of hyponatraemia, include fatigue, nausea, vomiting, giddiness and in the most severe cases circulatory failure.

Rogers et al. (1986) observed a mean decrease of 59 % in serum iron after a Ironman distance triathlon consisting of canoeing (20 km), cycling (90 km) and running (42 km). The reason for the decrease in serum iron is uncertain however 3 factors were hypothesized to be involved: 1) Iron loss through extreme sweating; 2) The presence of a pre-latent stage of chronic iron deficiency or 3) inhibition of iron release from stores during endurance exercise. These investigators also observed a 3 - fold increase in cortisol levels after the triathlon, which was hypothesized to be a function of the duration and intensity of exercise. Since cortisol levels after the race were negatively correlated with $\dot{V}O_2$ max the less aerobically fit competitors may have been exposed to greater physiological and/or psychological stress than triathletes with higher $\dot{V}O_2$ max values.

That endurance exercise can damage muscle tissue has been confirmed through a number of human muscle biopsy studies. As well, the presence of muscle enzymes in the blood is thought to be indirect evidence of muscle fiber damage due to repetitive exercise (Armstrong, 1986). It is possible that in repetitive endurance type exercise the muscle fibers are physically damaged and therefore allow leakage of muscle protein into extracellular space (Armstrong, 1986).

Elevations in the serum enzymes glutamate oxaloacetate transaminase (700 %), glutamate pyruvate transaminase (262 %) and lactate dehydrogenase (222 %) have been reported after completion of an Ironman triathlon (Holly et al., 1986). These increases, in the presence of aerobic muscle enzymes in the serum, appear to be related to increased release from working skeletal muscle. It was hypothesized that the duration and intensity of the Ironman race combined with the recruitment of a large proportion of muscle mass probably accounted for the large increases observed. Supporting this, Lesmes et al. (1987) reported significant elevation in the serum enzymes lactate dehydrogenase, creatine kinase and the ck-mb isozyme after ultramarathon runs and that a strong correlation between distance run and elevated enzyme levels ($r = 0.98$, $p <$

.001) strongly suggested an increase in muscle damage occurred as exercise distance increased.

Hemolysis, the breakdown of red blood cells due to physical exertion, has been reported to occur in runners, and its incidence appears to increase with exercise intensity and duration (Gilligan & Blumgart, 1941). Similarly, O'Toole et al. (1988) reported hemolysis to be indicated in 95 % of 95 triathletes entered in either a short course or Ironman distance triathlon, with the longer race causing a greater amount of hemolysis. These investigators hypothesized that intra-vascular hemolysis occurs as a result of mechanical trauma caused by repetitive footstrikes during running and thus in a longer race the higher number of footstrikes leads to increased hemolysis.

Besides the demands placed on triathletes as a result of the intensity and duration of the triathlon, there are also residual effects of exercising in one exercise mode on the response to exercise in another mode. Kreider et al. (1988) found that triathlon performance elicited cardiovascular and thermal adjustments not experienced when performing the events independently. These investigators found that compared to control cycling, prior swimming significantly decreased triathlon cycle work output ($\underline{p}$ < .05) and produced mean decreases in $\dot{V}O_2$, stroke volume, cardiac output, and mean arterial pressure and a mean increase in rectal temperature. In triathlon running there were significant ($p < .05$) increases in $\dot{V}O_2$, heart rate, arterial-venous O_2 difference and rectal temperature with decreases ($p < .05$) in stroke volume and mean arterial pressure when compared to a control run. Mayers et al. (1986), found maximal run time to exhaustion to decrease after prolonged cycle ergometry, however $\dot{V}O_2$ max was unaffected.

The demands of each discipline necessitate endurance training in each of the triathlon disciplines. The triathlete is presented with a training challenge in selecting the appropriate amount of training in each exercise mode since the effect of multiple modes of training on training specificity is not well understood. A number of researchers have attempted to describe current triathlon training practices and relate these practices to triathlon performance. Holly et al. (1986) observed that the top male finishers in an ultra-endurance triathlon performed a higher volume of training (45% more) than lower place finishers. A similar relationship was demonstrated for triathletes competing in a half triathlon with the top 5 competitors training 38% more than the rest of the competitors (Kohrt et al. 1987). O'Toole (1989) analyzed Hawaii Ironman competitors over 4 years (n = 323) and found that the fastest finishers swam greater weekly distances at faster paces than the majority of slower competitors, as well as completing more weekly mileage in cycling and running. She also reported a high amount of overlap in training practices between fast, medium and slow finishers. Holly et al. (1986) also found that the faster triathletes spent proportionately more time swim training than bike training and more time bike training than running. The daily training distances represented 71, 47 and 32 % respectively of the distances for the individual swim, bike and run segments of the race. A similar relationship was calculated using the data of Kohrt et al. (1987) with the daily training distances representing 158, 83, and 71 % (swim/bike/run) of the half triathlon training distances. Holly et al. (1986) felt that the reason swim training appeared to emerge as a critical training factor when in a race it only represents a small proportion of the total distance was due to the efficiency of swimming. An inefficient swimmer may expend twice the energy of an efficient swimmer during submaximal swimming.

Contrary to the findings of the above studies, Zinkgraff et al. (1986) found that the faster triathletes devote proportionate time to each of the three sports. The data of O'Toole et al. (1986) supports this (38% for swim, 24.1% for cycle and 24.5% for running) although the triathletes in this study did not appear to be of the same calibre as those rated " elite " in the Holly et al.

(1986) study.

Zinkgraff et al. (1986) did find significant correlations between training distance for each sport and associated performance time, possibly indicating that specificity in training is necessary to do well in each leg of the triathlon. Triathletes train less in each sport than their specialist counterparts (O'Toole et al., 1986; Kohrt et al., 1987) and one would therefore expect them not to perform as well in each sport as a specialist. Many of the same characteristics as endurance specialist would be expected however due to the high combined training volumes of triathletes and some possible cross-training effects.

Male triathletes have been reported to weigh 9 to 10 percent more than runners and similar to swimmers and cyclists with mean values reported between 68.9 and 74.7 kg (O'Toole et al., 1987; Kohrt et al., 1987; Kreider et al., 1988; Zinkgraf et al., 1986; Holly et al., 1986; Wells et al., 1987; Dengel et al., 1989; Burke et al., 1987) while female triathletes (mean = 60.3 - 63.1 kg) have been reported to weigh similar to swimmers and more than their cycling and running counterparts by 6 to 9 percent (O'Toole et al., 1987; Wells et al., 1987).

In comparing body composition of triathletes to endurance specialists the male and female triathlete are similar to the cycling,running and swimming specialists with mean values for males ranging from 8.6 to 10.5 and for females ranging from 10.2 to 14.8 % body fat (O'Toole et al., 1987; Kohrt et al., 1987; Burke et al., 1987; Kreider et al., 1988; Zinkgraf et al., 1986; Holly et al., 1986; Wells et al., 1987; Dengel et al., 1989). These values most likely reflect the high volumes of training performed by most triathletes.

$\dot{V}O_2$ max values for elite triathletes have been reported by several investigators for different modes of testing. Kohrt et al. (1987) tested swimming, cycling and running $\dot{V}O_2$ max values in 13 male triathletes. Treadmill $\dot{V}O_2$ max was found to average 60.5 ml * kg^{-1} * min^{-1} which ranges from 7 to 25 % less than values previously reported for endurance runners. Using this as a marker it was calculated that cycle $\dot{V}O_2$ max averaged 96% of the running value (57.9 ml * kg^{-1} * min^{-1}) and tethered swim $\dot{V}O_2$ max averaged 87% (52.5 ml * kg^{-1} * $min-^{1}$). Similarly, O'Toole et al. (1987) reported treadmill $\dot{V}O_2$ max scores of 68.8 ml * kg^{-1} * min^{-1} for male (5.5% above to 15 % below values reported for endurance runners) and 65.9 ml * kg^{-1} * min^{-1} for female triathletes with cycling $\dot{V}O_2$ max values only 3% less for males and 6% less for females. As stated before, in untrained subjects cycling tests are 5-8 % lower and swim tests 15 - 16 % lower than treadmill tests, while subjects trained in cycling or swimming can equal or exceed treadmill

$\dot{V}O_2$ max values. Therefore it was hypothesized that the triathletes in the above cited studies demonstrated some sport specific training effects and fall above untrained cyclists and swimmers but below athletes trained in these sports due to differences in training volumes for the specific sports . If a general training effect had occurred, equal improvement in all areas might have been expected. These studies did not document training practices so no definitive conclusions can be made. O'Toole et al. (1987) suggested a cross-training effect to occur since $\dot{V}O_2$ max values of triathletes in their study were similar to those of specialists even though the triathletes training volume were less in each of the sports. Other researchers have reported triathlete $\dot{V}O_2$ max values of 51.0 - 56.7 $ml * kg^{-1} * min^{-1}$ in tethered swimming (Dengel et al., 1989; Kreider et al., 1988), 56.3 - 67.8 $ml * kg^{-1} * min^{-1}$ in cycling (Dengel et al., 1989; Albrecht et al., 1986; Millard et al., 1986; O`Toole et al., 1987; Kreider et al., 1988) and 52.4 - 71.9 $ml * kg^{-1} * min^{-1}$ for treadmill running (Dengel et al., 1989; Delistraty et al., 1987; Albrecht et al., 1986; Millard et al., 1986; Holly et al., 1986; Kreider et al., 1988). The large variation in $\dot{V}O_2$ max values reported may be because of different training responses due to frequency, intensity and duration of training variations.

Little data exists on the AT of triathletes. Kohrt et al. (1987) reported the mean LT for a group of 7 triathletes to occur at 85% of treadmill $\dot{V}O_2$ max and 76% of cycle $\dot{V}O_2$ max. As stated before AT has been shown to occur 5 to 12 % closer to $\dot{V}O_2$ max on the treadmill as opposed to a cycle ergometer (Withers et al., 1981; Wiswell et al., 1979). The mean LT reported by Kohrt et al. (1987) falls within this range (9%). No studies examining the power outputs of triathletes at AT for swim, cycle or run were found and therefore no data relating this to performance of specific legs of the triathlon or overall performance were found. Since AT has been shown to be an excellent predictor of performance in long duration endurance events (MacDougall, 1977; p 41) it would be desirable to investigate this relationship in triathletes.

Besides AT, no data relating strength measures of triathletes to performance have been reported. Since the last two legs of a triathlon consist of cycling and running, leg strength would seem to be of importance.

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Appendix D

Raw Results

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OBS CODE SEX WEIGHT HEIGHT  BF  SVO2MA SVO2MR CVO2MA CVO2MR RVO2MA RVO2MR

  1   1   1   72.3   173.6 10.2  4.32    59.7   5.00   72.6   5.32   73.9
  2   2   1   76.9   182.3 10.3  3.28    42.8   4.02   52.3   4.27   55.3
  3   3   2   54.0   175.0 17.9  2.35    43.8   3.03   56.3   2.93   54.4
  4   4   1   74.3   176.2 16.8  3.74    50.3   4.61   60.9   4.68   63.2
  5   5   2   63.6   166.1 26.4  2.18    34.4   3.23   50.9   3.44   54.4
  6   6   1   74.7   179.1 10.4  3.81    50.7   4.42   58.6   4.55   61.4
  7   7   1   72.4   179.0  9.4  3.75    51.6   4.92   68.2   5.16   70.7
  8   8   1   66.2   168.4 14.6  3.65    55.2   4.23   63.4   4.76   72.1
  9   9   2   55.1   156.4 24.0  2.50    45.5   3.18   57.3   2.95   53.1
 10  10   1   86.6   185.0 20.8  3.74    43.2   4.67   53.9   4.75   54.4
 11  11   1   82.9   177.7 24.8  3.86    46.5   4.87   59.6   4.91   58.8
 12  12   2   60.4   169.7 23.2  2.15    35.8   3.25   54.0   3.12   51.8
 13  13   1   85.8   184.4 15.1  3.90    45.9   4.70   54.8   4.95   57.7
 14  14   1   68.7   177.1 11.8  4.21    61.8   4.33   62.9   4.57   67.0

OBS SATRES SATREL SATPER SATAB CATPO CATAB CATREL CATPER RATV RATREL RATAB

  1   4.5   50.3   84.4   3.64 305.1  4.14  57.7   82.8  10.5  60.0   4.32
  2   3.5   28.4   66.2   2.17 270.1  3.33  43.4   82.9   9.0  48.2   3.72
  3   2.5   28.8   65.8   1.55 198.5  2.27  42.1   74.8   8.5  42.1   2.27
  4   4.5   35.8   71.0   2.66 277.2  3.68  48.6   79.8  10.0  57.2   4.23
  5   2.3   22.9   66.5   1.45 192.8  2.40  37.7   74.2   8.0  43.8   2.77
  6   4.5   35.7   70.4   2.68 305.3  3.65  48.6   82.5   9.5  53.7   3.98
  7   4.0   39.3   76.3   2.86 303.7  3.91  54.2   79.5   9.5  53.7   3.90
  8   5.5   47.4   85.8   3.13 230.9  2.94  44.1   69.5   8.5  53.0   3.50
  9   3.5   27.3   60.0   1.50 183.1  2.50  45.1   78.7   8.5  48.5   2.69
 10   4.5   23.5   54.5   2.04 290.4  3.60  41.6   77.2   9.5  47.4   4.14
 11   5.5   37.7   81.2   3.13 333.3  3.96  48.5   81.4  10.5  51.1   4.26
 12   2.5   30.0   83.5   1.80 169.6  2.10  34.9   64.5   8.0  42.8   2.57
 13   5.0   32.9   71.9   2.80 261.2  3.74  43.6   79.6   9.5  53.6   4.60
 14   4.5   37.3   60.5   2.55 270.8  3.73  54.1   86.1  10.5  59.8   4.08

OBS RATPER LSTEXNM LSTENMKG LSTFNM LSTFNMKG SVTVO2 CVTVO2 RVTVO2 RSVO2 RCVO2

  1  81.2   203.0     2.81    114.0    1.58     84.3   82.8   81.2   81.1   94
  2  87.2   238.0     3.09    126.0    1.64     66.2   82.8   87.1   76.8   94
  3  77.4   155.5     2.88    108.0    2.00     65.8   74.8   77.4   80.2  103
  4  90.4   150.0     2.02    106.0    1.43     71.0   79.8   90.4   80.0   98
  5  80.5   131.5     2.07     82.0    1.29     66.5   74.2   80.5   63.4   94
  6  87.5   193.5     2.59    147.0    1.97     70.4   82.5   87.5   83.7   97
  7  75.5   237.5     3.28    141.0    1.95     74.4   79.5   75.5   72.6   95
  8  73.6   130.5     1.96    105.5    1.59     85.8   69.5   73.5   76.6   88
  9  91.3   115.0     2.09     89.5    1.62     60.0   78.7   91.3   84.8  107
 10  87.2   207.0     2.39    122.5    1.41     54.5   77.2   87.2   78.9   98
 11  86.8   208.5     2.52    142.0    1.71     81.2   81.4   86.8   78.6   99
 12  82.5   125.5     2.08     64.5    1.07     83.6   64.5   82.5   69.1  104
 13  92.9   215.0     2.51    122.0    1.42     71.8   79.5   92.9   78.7   94
 14  89.3   211.5     3.08    136.5    1.99     60.5   86.1   89.3   92.3   94
```

OBS	CODE	SEX	WEIGHT	HEIGHT	BF	SVO2MA	SVO2MR	CVO2MA	CVO2MR	RVO2MA	RVO2MR
15	15	1	61.8	176.2	10.0	3.26	52.8	4.47	71.9	4.42	71.7
16	16	2	58.0	165.7	25.2	1.54	26.8	2.45	42.4	2.61	44.7
17	17	1	75.0	187.0	10.4	3.11	41.2	4.44	58.8	4.91	66.2
18	18	2	58.3	165.7	23.5	2.40	41.4	2.94	50.1	2.98	50.8
19	19	1	87.8	186.3	14.3	4.13	46.5	4.52	51.0	5.09	58.7
20	20	1	72.8	176.3	10.6	3.83	52.6	4.47	61.6	5.02	68.9
21	21	1	83.9	191.1	13.6	4.30	51.3	4.67	55.0	4.72	56.3
22	22	1	93.0	189.4	13.5	4.77	51.7	5.49	58.0	5.63	60.5
23	23	2	65.9	166.2	35.0	2.58	39.1	3.09	47.0	3.34	50.9
24	24	1	61.0	171.1	9.8	3.14	51.9	3.97	64.7	4.53	73.7
25	25	1	76.0	179.4	14.9	3.20	42.2	4.04	52.7	4.31	56.9

OBS	SATRES	SATREL	SATPER	SATAB	CATPO	CATAB	CATREL	CATPER	RATV	RATREL	RATAB
15	3.5	35.5	67.2	2.19	267.6	3.19	51.3	71.3	11.0	62.3	3.84
16	2.0	21.7	81.2	1.25	175.2	1.88	32.5	76.6	6.0	39.1	2.28
17	4.5	30.8	74.7	2.32	277.2	3.39	44.9	76.4	11.0	59.4	4.41
18	3.5	35.3	85.4	2.05	176.5	2.21	37.6	75.1	9.0	42.5	2.49
19	4.0	38.3	82.4	3.40	286.8	3.86	43.6	85.4	9.5	50.1	4.34
20	4.0	35.7	67.9	2.60	312.3	3.85	53.1	86.2	9.5	55.1	4.02
21	4.5	39.0	76.1	3.27	327.7	3.93	46.2	84.1	9.5	50.1	4.20
22	4.5	31.5	60.8	2.90	364.7	4.77	50.4	86.8	10.0	52.8	4.92
23	3.7	34.2	87.3	2.25	183.8	2.46	37.5	79.7	8.5	46.9	3.07
24	4.0	34.7	66.8	2.10	260.3	3.24	52.8	81.7	10.5	57.2	3.52
25	4.0	31.2	74.1	2.37	305.9	3.75	48.9	92.8	9.0	46.6	3.53

OBS	RATPER	LSTEXNM	LSTENMKG	LSTFNM	LSTFNMKG	SVTVO2	CVTVO2	RVTVO2	RSVO2	RCVO2
15	86.9	191.1	2.62	122.2	1.67	67.2	71.3	86.9	72.8	101
16	87.5	119.0	2.05	71.5	1.23	81.2	76.6	87.5	59.1	94
17	89.8	152.0	2.03	122.5	1.63	74.7	76.4	89.8	63.2	90
18	83.6	167.0	2.86	94.5	1.62	85.5	75.1	83.6	80.6	98
19	85.3	319.0	3.63	212.5	2.42	82.4	85.4	85.3	81.1	88
20	80.0	282.0	3.87	164.0	2.25	67.9	86.2	80.0	76.3	88
21	89.0	211.5	2.52	166.0	1.98	76.1	84.1	89.0	91.0	99
22	87.3	254.0	2.73	177.0	1.90	60.8	86.8	87.3	84.6	97
23	92.0	147.5	2.24	81.0	1.23	87.4	79.7	92.0	83.5	92
24	77.6	191.1	2.62	122.2	1.67	66.8	81.7	77.6	69.3	87
25	82.0	221.0	2.91	115.0	1.51	74.1	92.8	82.0	74.3	93

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