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ORIGINAL ARTICLE

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Relationship of exercise test variables to cycling performance in an Ironman triathlon

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Abstract The purpose of this study was, firstly, to investigate the intensity of exercise performanceof highly trained ultra-endurance triathletes during the cycling portion of an Ironman triathlon, and, secondly, to examine the anaerobic threshold and its relationship to this performance. Following a peak oxygen consumption ($\dot{V}O_{2peak}$) test on a cycle ergometer to determine the heart rate ($HR_{Th,vent}$) and power output ($PO_{Th,vent}$) at the ventilatory threshold (Th_{vent}), 11 highly trained male triathletes [mean (SEM) age 35.8 (1.6) years, body fat 11.7 (1.2)%. $\dot{V}O_{2peak}$ 67.5 (1.0) ml·kg^{-1}·min^{-1}] who were participating in an Ironman triathlon, in random order: (1) cycled at their $PO_{Th,vent}$ ($Bi_{Th,vent}$) until they were exhausted, and (2) cycled for 5 h at a self-selected intensity (Bi_{SSI}). Cycling power output (PO), oxygen uptake ($\dot{V}O_2$), heart rate (HR) and blood lactate concentration ($[La^-]_b$) were recorded at regular intervals during these trials, while performance HR was recorded during the cycling phase of the Ironman triathlon. Significantly greater ($P < 0.05$) values were attained during $Bi_{Th,vent}$ than during Bi_{SSI} for PO [274 (9) compared to 188 (9) W], $\dot{V}O_2$ [3.61 (0.15) compared to 2.64 (0.09) l·min^{-1}], and $[La^-]_b$ [6.7 (0.8) compared to 2.8 (0.4) mmol·l^{-1}]. Moreover, mean HR during the Ironman triathlon cycle phase [146.3 (2.4) beats·min^{-1}; $n = 7$] was significantly greater than mean HR during Bi_{SSI} [130 (4) beats·min^{-1}], and significantly less than mean HR during $Bi_{Th,vent}$ [159 (3) beats·min^{-1}; all $P < 0.05$]. However, HR during the cycle portion of the Ironman triathlon was highly related to ($r = 0.873$; $P < 0.05$) and not significantly different to $HR_{Th,vent}$ [150 (4) beats·min^{-1}]. These data suggest that ultra-endurance triathletes cycle during the Ironman triathlon at a HR intensity that approximates to $HR_{Th,vent}$, but at a PO that is significantly below $PO_{Th,vent}$.

Keywords Ultra-endurance · Anaerobic threshold · Ventilatory threshold · Lactate · Critical performance intensity

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Introduction

Despite considerable research examining physiological responses to the physical stresses inherent in the Ironman triathlon (Laursen and Rhodes 2001; Laursen et al. 2000; O'Toole and Douglas 1995; Speedy et al. 1999), relatively little information is available concerning the exercise intensity that can be maintained throughout these multiple component events (Laursen and Rhodes 2001; O'Toole et al. 1989, 1998). The so-called anaerobic threshold (Th_{an}) has long been considered to be the critical performance intensity that an endurance athlete can maintain throughout an endurance event (Rhodes and McKenzie 1984; Wasserman 1984). At the Olympic triathlon distance (1.5 km swimming, 40 km cycling, 10 km running), strong relationships with the ventilatory threshold (Th_{vent}) have been shown during both the cycling and running stages (De Vito et al. 1995; Schabort et al. 2000; Sleivert and Wenger 1993; Zhou et al. 1997). However, studies examining performance intensity during the Ironman triathlon (3.8 km swimming, 180 km cycling, 42.2 km running) have provided equivocal results. While some authors have reported good relationships between performance heart rate (HR) during the cycling portion of the Ironman triathlon and the HR corresponding to Th_{vent} ($HR_{Th,vent}$) (O'Toole et al. 1987a; Roalstad et al. 1987), another study has shown a weaker relationship ($r=0.06$ to –0.58) between Th_{vent} variables and Ironman performance during cycling (O'Toole et al. 1989). Laboratory assessments of cycling time to exhaustion at the power output associated with the Th_{an} have been reported to range from 48 to 255 min depending on training status, the provision of fluids and carbohydrates, and whether the lactate threshold or Th_{vent} were used to estimate the Th_{an} (Aunola et al. 1990; Davis et al. 1992; Loat and Rhodes 1996). It seems unrealistic, therefore, to perform the 180 km cycling phase of the Ironman triathlon at the Th_{an}, where ultra-endurance factors (i.e. changes in substrate utilization, fluid and electrolyte imbalances) may contribute to the detriment in intensity during prolonged endurance performance. Nevertheless, ultra-endurance triathletes probably choose to perform at some critical exercise intensity during these events, which could be relative to the Th_{an} (Laursen and Rhodes 2001). Indeed, a moderate correlation ($r=0.61$; $P<0.05$) has been shown between percentage peak oxygen uptake ($\dot{V}O_{2peak}$) at 10 W below the mean Th_{vent} exercise intensity and cycling finishing times during the Hawaiian Ironman (O'Toole et al. 1989). This finding provides evidence to suggest that an *ultra-endurance threshold*, or an optimal performance intensity, might exist at a relative intensity below the Th_{an} (Laursen and Rhodes 2001).

The purpose of the present study was, therefore, to investigate the exercise intensity at which ultra-endurance triathletes cycle during an Ironman triathlon. In particular, the duration for which ultra-endurance triathletes could cycle at their power output (PO) corresponding to their Th_{vent} ($PO_{Th,vent}$, $Bi_{Th,vent}$) was examined in comparison to the PO chosen during 5 h of cycling at a self-selected intensity (Bi_{SSI}). In addition, the HR during these trials was compared to cycling HR during the Ironman Canada triathlon (IMC). Our hypotheses were that:

1. Triathletes would select a mean PO during Bi_{SSI} which would be less than, and relative to, their $PO_{Th,vent}$ (i.e. our proposed *ultra-endurance threshold*; Laursen and Rhodes 2001)
2. There would be a homogenous set of endurance times for the $Bi_{Th,vent}$ trial (approximately 2–3 h).

Methods

Subjects

A group of 11 male ultra-endurance triathletes [mean (SEM)] [age 35.8 (1.6) years, height 176.7 (2.3) cm, body mass 68.9 (2.2) kg, body fat 11.7 (1.2)%, $\dot{V}O_{2peak}$ 67.5 (1.0) $ml \cdot kg^{-1} \cdot min^{-1}$] were recruited 4–6 weeks prior to the 1999 IMC (Penticton, British Columbia, Canada). The inclusion criteria consisted of a cycling $\dot{V}O_{2peak}$ greater than 60 $ml \cdot kg^{-1} \cdot min^{-1}$ and having previously completed a minimum of one Ironman triathlon distance event under 11 h:30 min. Before the tests, all risks and benefits were thoroughly explained and written informed consent was obtained in accordance with the Guidelines for Ethical Review at The University of British Columbia. This experiment complied with the current laws of Canada.

Test procedures

Prior to all tests, subjects were instructed to refrain from heavy exercise for 24 h, and to prepare as they would for an ultra-endurance race. Subjects reported to a controlled environment laboratory held in similar conditions (approximately 21°C, 40%–60% relative humidity, barometric pressure 760–770 mmHg) at the same time of day for all tests (Hill et al. 1998). The triathletes were asked to keep their eating habits constant before all tests and to avoid consuming food within 2 h of exercise. During all laboratory sessions, expired gases were collected and analysed using a Vmax metabolic cart (V6200, SensorMedics Corporation). The gas analysers and ventilometer were calibrated immediately before and validated after each test in accordance with the manufacturer's instructions. The HR was measured using a Polar HR monitor (Vantage NV, Polar Electro, Finland) and cycling PO and cadence were measured on an electronically braked cycle ergometer (SensorMedics 800 Ergometer) modified with clip-in pedals and low profile racing handlebars. The saddle and handlebar positions of the cycle ergometer were adjusted to resemble the subject's own bicycle, and the subjects warmed-up at self-selected intensities for 5 min. All sessions were preceded by an explanation of the test procedures followed by the physiological warm-up against a light resistance load. At least 48 h following the $\dot{V}O_{2peak}$ test, subjects performed in random order, at least 1 week apart: (1)$Bi_{Th,vent}$ and (2) Bi_{SSI}.

Another $\dot{V}O_{2peak}$ test was performed 2 weeks prior to the Ironman triathlon to ensure that the variables measured during the $\dot{V}O_{2peak}$ test had not changed. Before the first session, consent forms were signed, followed by baseline measurements of age, height, body mass and percentage body fat from underwater weighing.

Progressive exercise test

The incremental test commenced at an initial intensity of 100 W, increasing thereafter by 30 $W \cdot min^{-1}$ until the subjects were fatigued. The $\dot{V}O_{2peak}$ was defined as:

1. An oxygen consumption ($\dot{V}O_2$) ceasing to increase with rising exercise intensity, the last two values agreeing to within 2 $ml \cdot kg^{-1}$ $\cdot$min–1
2. The attainment of 90% of age predicted maximal heart rate (HR_{max})
3. A respiratory exchange ratio greater than 1.10

The Th_{vent} was determined from the excess CO_2 elimination curve (Frangolias and Rhodes 1996) from visual inspection by two independent reviewers. In the event of a disagreement, a change in the oxygen cost of ventilation curve (Takano et al. 1991) was used to indentify the threshold point.

Cycling until fatigued at the PO of Th_{vent}

Following a 5 min warm up at 100 W, the subject began cycling at $PO_{Th,vent}$. The $\dot{V}O_2$ was measured for 5 min after 5 min exercise, and then for 5 min every 30 min thereafter (i.e. at 30, 60, 90 min, etc.). Borg's rating of perceived exertion (RPE, Borg 1982) and blood lactate concentration ($[La^-]_b$) were recorded every 30 min, while HR was recorded every 60 s . When the athlete felt that he could not maintain his cadence for more than 5 min, final measurements of $\dot{V}O_2$, $[La^-]_b$, and RPE were taken. The subjects had access to water and an 8% carbohydrate-electrolyte beverage

(Shaklee Performance); the quantities consumed of each were recorded. Fatigue was defined either by an inability to maintain a cadence of at least 50 r.p.m. or the subject's termination of the test. After towelling dry and wearing only cycling shorts, body mass was recorded post-test to determine any fluid loss or gain.

Cycling for 5 h at a self-selected intensity

The Bi_{SSI} protocol was identical to $Bi_{Th,vent}$ except that changes in PO were based on what the subject felt was an intensity they could cycle at for 5 h, presumably similar to that of the Ironman bike course. A limit was not put on the number of times that intensity could be adjusted, but this intensity was relatively constant throughout Bi_{SSI} (Fig. 1).

Canadian Ironman triathlon

Prior to IMC, the subjects were fitted with HR monitors, and HR readings during the race were stored at 60 s increments. The HR monitors were retrieved from the athletes following IMC and data was downloaded at the earliest opportunity. All race times were measured electronically by SportStats, the official timers for the IMC.

Statistical analysis

A repeated measurements analysis of variance (ANOVA) was used to compare the dependent measurements of $\dot{V}O_2$, HR, PO, and $[La^-]_b$ during $Bi_{Th,vent}$ and Bi_{SSI} over time. Pearson product moment analyses examined relationships between $HR_{Th,vent}$ and mean HR during IMC, $Bi_{Th,vent}$, and Bi_{SSI}. All statistical analyses were carried out using SPSS 8.0 for Windows (SPSS Inc., Chicago, Ill.) and the α level was set at 0.05. The results are expressed as mean (SEM).

Results

There were no significant differences found between any of the measured variables during the two $\dot{V}O_{2peak}$ tests. Therefore, values for the progressive exercise test are presented as a mean score of the two tests (Table 1). The amount of training during the test period prior to IMC was 16.3 (1.0) h·week^{-1}, which included 2.7 (0.5) h·week^{-1} of swimming, 8.5 (0.6) h·week^{-1} of cycling, and 4.5 (0.5) h·week^{-1} of running. The mean performance time for IMC was 11 h:17.2 (15.9) min; broken down into the swimming, cycling, and running portions this equated to 1 h:7.3 (1.7) min; 5 h:31.3 (3.7) min; and 4 h:30.4 (12.2) min, respectively.

Based upon the results of $Bi_{Th,vent}$, 3 triathletes could not perform at their $PO_{Th,vent}$ for longer than 1 h [32.0 (9.7) min, $n=3$]. Therefore, their results were omitted from the statistical comparisons (group×time) between $Bi_{Th,vent}$ and Bi_{SSI}. The remaining 8 subjects had an endurance time for the $Bi_{Th,vent}$ trial of 2 h:10.7 (18.6) min (range: 12 min–3 h:40 min). In contrast, all subjects completed the Bi_{SSI} trial. The dependent variables of $\dot{V}O_2$, PO, HR, $[La^-]_b$, and RPE were significantly greater during $Bi_{Th,vent}$ compared to Bi_{SSI} (Table 2; $P<0.05$). The measurements of $\dot{V}O_2$, PO, and HR are also presented as percentages of their maxima, and as percentages of Th_{vent}, for $Bi_{Th,vent}$ and Bi_{SSI} (Table 3). Body mass losses for $Bi_{Th,vent}$ [0.5 (0.2) kg] and Bi_{SSI} [0.3 (0.3) kg] were not signifi-

Table 1. Measurements [mean (SEM)] of oxygen consumption ($\dot{V}O_2$), power output (*PO*), and heart rate (*HR*) at the ventilatory threshold (*Th*$_{vent}$) and at peak exercise (*Peak*) during the progressive cycling test

	$\dot{V}O_2$ (l·min^{-1})	PO	HR
Th_{vent}	3.30 (0.08)	287 (9)	148.7 (3.4)
Peak	4.68 (0.16)	437 (18)	176.2 (3.3)

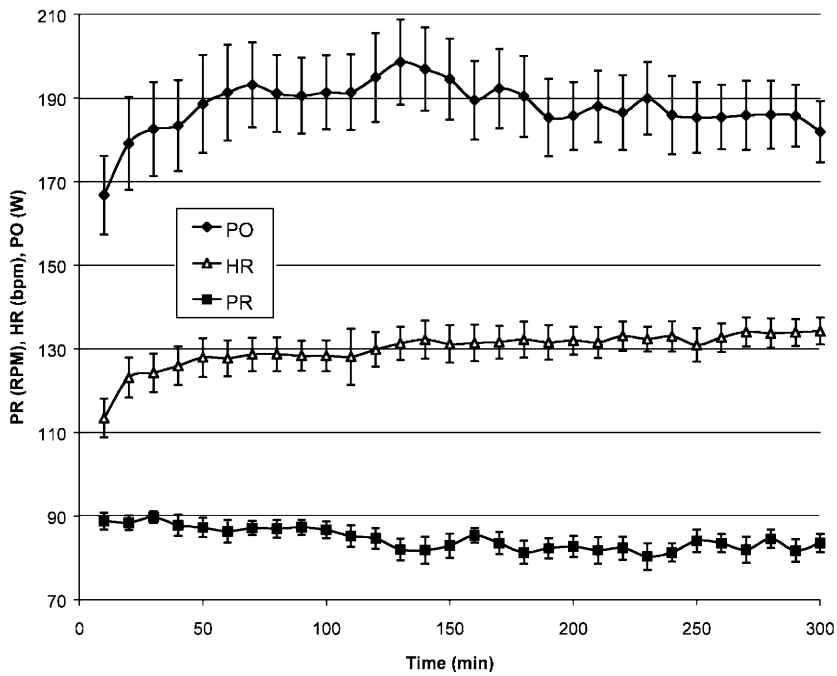

Fig. 1. Comparison of the changes in power output (*PO*), heart rate (*HR*), and pedalling rate (*PR*) with respect to time for the 5 h self-selected intensity cycling time trial ($n=11$)

Table 2. Mean (SEM) values of oxygen uptake ($\dot{V}O_2$), power output (*PO*), heart rate (*HR*), blood lactate concentration ($[La^-]_b$) and rating of perceived exertion (*RPE*) measured during the ride to fatigue at the PO of the ventilatory threshold ($Bi_{Th,vent}$) and during 5 h of cycling at a self-selected intensity (Bi_{SSI})

Variable ($n=8$)	$Bi_{Th,vent}$	Bi_{SSI}
$\dot{V}O_2$ ($l \cdot min^{-1}$)	3.61 (0.15)*	2.64 (0.09)
PO (W)	274 (9)*	188 (9)
HR ($beats \cdot min^{-1}$)	159 (3)*	130 (4)
$[La^-]_b$ ($mmol \cdot l^{-1}$)	6.7 (0.8)*	2.8 (0.4)
RPE (Borg units)	16.6 (0.4)*	13.5 (0.5)

*$Bi_{Th,vent}$ significantly greater than Bi_{SSI} ($P<0.05$)

Table 3. Measurements of oxygen uptake ($\dot{V}O_2$), power output (*PO*), and heart rate (*HR*) for the ride to fatigue at the PO of the ventilatory threshold ($Bi_{Th,vent}$) and 5 h of cycling at a self-selected intensity (Bi_{SSI}) expressed as percentages of their peak value and ventilatory threshold (Th_{vent}) value ($n=8$)

Variable	$Bi_{Th,vent}$	Bi_{SSI}
% of Peak		
$\dot{V}O_2$	76 (4)%*	55 (4)%
PO	66 (1)%*	45 (2)%
HR	89 (1)%*	73 (1)%
% of Th_{vent}		
$\dot{V}O_2$	111 (3)%*	81 (3)%
PO	100 (0)%*	67 (3)%
HR	105 (2)%*	87 (2)%

*$Bi_{Th,vent}$ significantly greater than Bi_{SSI} ($P<0.05$)

cantly different between trials or from baseline measurements. Significantly more ($P<0.05$) fluid and carbohydrate were consumed during Bi_{SSI} [4.92 (0.33) l and 499 (25) g] compared to $Bi_{Th,vent}$ [1.99 (0.52) l and 176 (42) g].

In addition to the 3 subjects excluded for not completing a minimum of 60 min during the $Bi_{Th,vent}$ trial, three data sets were lost during the IMC due to malfunction of the HR monitors. Thus, comparisons between HR during $Bi_{Th,vent}$, Bi_{SSI}, and IMC cycling performance were only available for 5 subjects (i.e. group×time). Comparisons between $HR_{Th,vent}$ and HR during Bi_{SSI}, $Bi_{Th,vent}$ and IMC were available for 7 subjects. The$HR_{Th,vent}$ demonstrated significant relationships ($P<0.05$) with mean IMC cycling HR ($r=0.873$), Bi_{SSI} HR ($r=0.770$), and $Bi_{Th,vent}$ HR ($r=0.825$). The HR during the cycling portion of the IMC was significantly greater than HR during Bi_{SSI} ($P<0.05$; $n=7$; Fig. 2). There were no relationships between endurance time during $Bi_{Th,vent}$ and any of our measured variables, with one exception. When a significant outlier was removed (Howell 1997), there was a significant inverse relationship shown between $Bi_{Th,vent}$ endurance time and the difference between $PO_{Th,vent}$ and the mean self-selected PO measured during Bi_{SSI} ($r=-0.754$; $P<0.05$; Fig. 3).

Discussion

The main finding in the present study was that Bi_{SSI} in the laboratory was performed at a PO that was significantly below $PO_{Th,vent}$ (Table 2; $P<0.05$); The $\dot{V}O_2$, HR, $[La^-]_b$, and RPE measured during $Bi_{Th,vent}$ were all significantly greater than those during Bi_{SSI} (Tables 2, 3; $P<0.05$). In addition, performance at $PO_{Th,vent}$ (i.e. $Bi_{Th,vent}$) was not maintained for 5 h by any of the

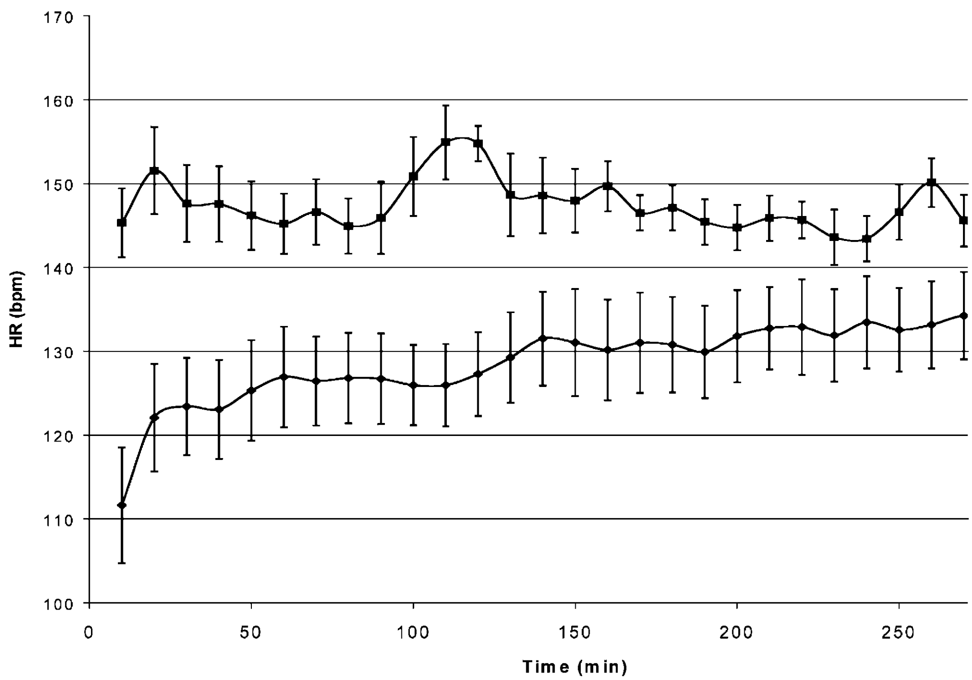

Fig. 2. Comparison of the changes in heart rate (*HR*) with respect to time for 5 h of cycling during a self-selected intensity trial (Bi_{SSI}, lower trace) and the first 300 min of the Ironman Canada triathlon (IMC, upper trace). The HR during IMC was significantly greater than HR during Bi_{SSI} ($P<0.05$; $n=7$)

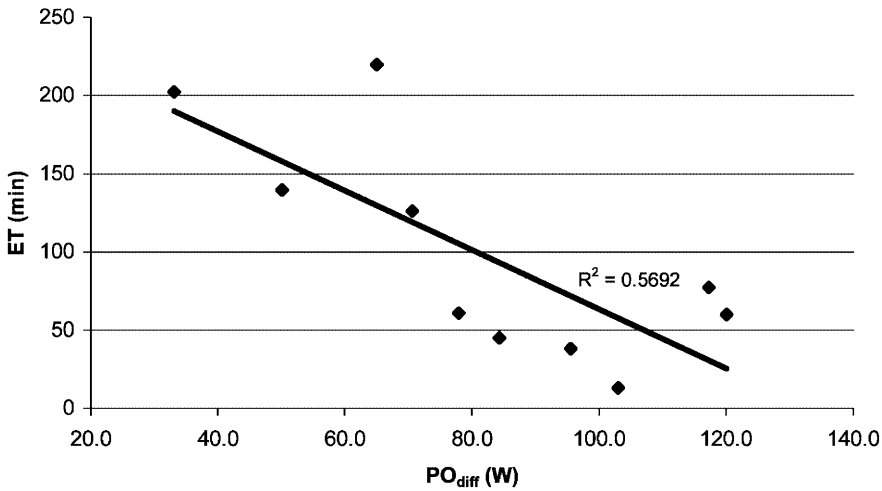

Fig. 3. Endurance time (*ET*) to fatigue during the cycling until exhausted at the power output (PO) of the ventilatory threshold trial plotted against the difference in power output (PO_{diff}) between that at the ventilatory threshold and the self-selected PO chosen during the trial of cycling at a self-selected intensity ($r = -0.754$; $P < 0.05$; $n = 10$; see text for details)

subjects [mean $Bi_{Th,vent}$ time: 2 h:10.7 (18.6) min; Fig. 3]. Moreover, HR during the cycling phase of IMC [146.3 (2.4) beats·min^{-1}] was significantly less ($P < 0.05$) than HR during $Bi_{Th,vent}$ [159 (3) beats·min^{-1}]. Collectively, these findings suggest that ultra-endurance triathletes do not cycle during the Ironman triathlon at their $PO_{Th,vent}$ as measured during a progressive cycling test. These findings are important, as they cannot be explained by conventional models of exercise physiology (Noakes 2000).

While the concept of an Th_{an} has been debated in the past (Brooks 1985; Davis 1985), the main support for this concept has come from studies showing strong correlations with exercise performance at the lactate or ventilatory turnpoints (Coyle et al. 1991; Farrell et al. 1979; Hopkins and McKenzie 1994; Rhodes and McKenzie 1984). However, for the Th_{an} hypothesis to be correct, then similar endurance times should be found in a homogenous group of highly trained endurance athletes asked to perform to exhaustion at their Th_{an}. In accordance with conventional models of exercise physiology (Noakes 2000), performance in highly trained endurance athletes should presumably be maintained until significant glycogen depletion occurs. Indeed, we hypothesized that we would find a mean endurance time for the $Bi_{Th,vent}$ trial somewhere in the 2–3 h range, with a low variance. However, our vast range of endurance times shown during the $Bi_{Th,vent}$ trial (i.e. Fig. 3), similar to that shown in other studies (Aunola et al. 1990; Davis et al. 1992; Loat and Rhodes 1996), does not support this theory.

According to the Th_{an} hypothesis, exercise that is performed at an intensity just below that which avoids the sharp rise in muscle and blood lactate concentrations is maintainable for prolonged periods (Wasserman 1984). Consequently, this model also implies that muscle or $[La^-]_b$ is the principle determinant of the pacing strategy in an endurance event. However, as we have shown (Table 2), this was not the case. The $[La^-]_b$ was significantly higher during the $Bi_{Th,vent}$ trial compared to the Bi_{SSI} trial ($P < 0.05$) – the exact opposite of the prediction. Thus, our findings do not lend support to the Th_{an} hypothesis, as $[La^-]_b$ could not predict the pacing strategy in our exercise trials. Nevertheless, it is possible that our Th_{vent} calculations might not have precisely identified the lactate threshold in our subjects (Green et al. 1983). Indeed, $\dot{V}O_2$ and HR measured during $Bi_{Th,vent}$ were 7% and 9% above Th_{vent}, respectively (Table 3). When exercise occurs above Th_{vent}, the $\dot{V}O_2$ slow component phenomenon (Barstow and Mole 1991; Xu and Rhodes 1999) causes $\dot{V}O_2$ to rise for several minutes until either a delayed but elevated steady state is attained, or exhaustion occurs (Jones et al. 1999), possibly due to an increased recruitment of type II motor units (Barstow et al. 1996). Moreover, when a significant outlier was removed from our data (Howell 1997), there was a significant inverse relationship shown between $Bi_{Th,vent}$ endurance time and the difference between the mean PO during Bi_{SSI} and that during $Bi_{Th,vent}$ PO ($r = -0.754$; $P < 0.05$; Fig. 3). Thus, the closer the subject came to performing at their $PO_{Th,vent}$ during the Bi_{SSI} trial, the longer they were able to exercise during $Bi_{Th,vent}$. This finding could also suggest that we incorrectly estimated the Th_{an} in these subjects.

In spite of these findings, a novel approach may be to interpret our observations in the context of more contemporary concepts relating to the exercise fatigue process (Noakes 2000; Noakes et al. 2001). We began our investigation into the pacing strategies undertaken by highly trained ultra-endurance triathletes through an examination of the physiological responses (i.e. $\%\dot{V}O_{2peak}$, $[La^-]_b$, HR, etc.) to Bi_{SSI} (closed loop design) and the exercise time to fatigue at the Th_{an} (open loop design). Indeed, the physiological responses during these two trials were significantly different to one another ($P < 0.05$; Tables 2, 3), and therefore neither $[La^-]_b$ nor Th_{an} appeared to determine the pacing strategy during prolonged ultra-endurance cycling. Moreover, we could not find evidence of an *ultra-endurance threshold*, or a consistent performance for the Bi_{SSI} at a relative intensity below the Th_{an} as we originally hypothesized (Laursen and Rhodes 2001).

Thus, if exercise scientists are to contribute further to the endurance performance outcomes of elite athletes, we must continue our search for determinants of pacing strategy and fatigue in areas other than those described by conventional models of exercise physiology (Noakes 2000; Noakes et al. 2001).

Noakes (2000) and Noakes et al. (2001) have recently proposed that a central governor may exist, probably either in the brain or in the heart, that would monitor the fatigue process and terminate high-intensity endurance exercise before an ischaemic response could occur in vital organs. While these authors (Noakes 2000; Noakes et al. 2001) offer many hypotheses as to how this might occur, one theory postulates that low levels of arterial oxygen saturation (S_aO_2) might be detected by some "yet-to-be-discovered" sensors in either the heart or the brain. While this appears to be an attractive hypothesis, we did actually measure S_aO_2 using pulse oximetry during our trials as part of a companion paper that evaluated the ventilatory response to prolonged cycling and running in these triathletes (Laursen et al. 2002). We found that S_aO_2 was statistically unchanged from levels at rest [97 (1)%] to exhaustion [96 (1)%] during $Bi_{Th,vent}$. These moderately high levels of S_aO_2 at exhaustion during $Bi_{Th,vent}$ would not lend support to the theory that a central governor terminates high-intensity endurance exercise based on low levels of S_aO_2. When we asked our subjects why they had to stop exercising during the $Bi_{Th,vent}$ trial, nearly all responded that fatigue was locally felt in their legs, and that they could no longer maintain the required pedalling rate. This evidence points more to traditional mechanisms of fatigue occurring during high-intensity exercise, namely, the cardiovascular/anaerobic model, and the energy supply/energy depletion model (Noakes 2000). These models suggest that high concentrations of lactate, or low levels of pH might alter actin-myosin cross-bridge cycling, or that adenosine triphosphate (ATP) demand could exceed ATP supply in the cytosol. The finding of a significant relationship between skeletal muscle buffering capacity and 40 km time-trial performance demonstrates the importance of the peripheral H^+ ion buffering mechanisms for successful endurance performance in highly trained athletes (Weston et al. 1997).

Another hypothesis that has recently surfaced to explain peripheral fatigue is "neuromuscular fatigue". In this model, the brain would act as the "central governor" (St Clair Gibson et al. 2001a). Most recently, St Clair Gibson et al. (2001b) have suggested that changes in neuromuscular activity might be due to commands generated in higher cortical structures, or in response to afferent input from metabolic changes in the peripheral organs. Using a closed loop design (100 km time trial, interspersed with 1 km and 4 km sprints), these authors found that neuromuscular activity in the peripheral skeletal muscles (as assessed by integrated electromyogram) fell in parallel with the reduced PO during the 1 km and 4 km sprints (St Clair Gibson et al. 2001b). This study provided evidence that a central neural governing command might exist to reduce the active muscle recruited during prolonged endurance exercise, in accordance with the task at hand (i.e. closed loop exercise trial) together with afferent feedback from metabolic processes. This could help to explain the large variance in time to exhaustion during our $Bi_{Th,vent}$ trial, as our "open loop design" would make our subjects rely solely on afferent feedback; "the task at hand" not being completely known. The high coefficient of variation found in open loop design studies and the low coefficient of variation found in closed loop design studies (Hopkins et al. 2001) further supports the importance placed on "knowing the expected outcome" by a central programmer (i.e. the brain). Further research is warranted in this area.

While our data clearly shows that ultra-endurance triathletes do not cycle during the Ironman triathlon at their $PO_{Th,vent}$, it would appear that they do cycle during this phase at a HR intensity near $HR_{Th,vent}$. The HR measured during the cycling phase of IMC [84.6 (1.3)% HR_{max}; Fig. 2] was associated with ($r = 0.866$; $P < 0.05$), and not significantly different to $HR_{Th,vent}$ (Table 1). Both Roalstad et al. (1987) and O'Toole et al. (1987a) independently reported that the cycling portion of the Hawaiian Ironman is performed at an exercise intensity of approximately 75% HR_{max}. O'Toole et al. (1987a) observed that 75% HR_{max} corresponded to Th_{vent}, suggesting that the cycling portion of the Ironman is completed at an exercise intensity which approximates $HR_{Th,vent}$.

Another finding in the present study was that a laboratory simulation of the Ironman triathlon cycle phase (i.e. Bi_{SSI}) was performed at a significantly lower HR than that achieved during the cycle phase of the IMC (Fig. 1; $P < 0.05$). This occurred despite the fact that subjects were asked to mimic the intensity of their Ironman cycling. While it could be argued that differences between these two trials may be explained by the fact that a 3.8 km swim did not precede Bi_{SSI} in the present study (De Vito et al. 1995), we have previously shown that 3,000 m of swimming had no significant effect on performance and physiological measurements during 3 h of subsequent cycling (Laursen et al. 2000). Better explanations for this observation of an increased HR during IMC compared to Bi_{SSI} include the psychological effects of a race environment (Lambert et al. 1998; Selley et al. 1995), and the increased thermoregulatory demands caused by a warmer climate (i.e. approximately 22°C in the laboratory compared to 30°C during the IMC) (Coyle and Montain 1992). The intensity of the Bi_{SSI} trial [55.4 (3.5% $\dot{V}O_{2peak}$) was similar to that shown by O'Toole et al. (1987b) during a 5 h laboratory cycle ride. Due to the fact that mean HR during the cycle phase of the Ironman triathlon was significantly greater than HR measured during Bi_{SSI}, it is difficult to ascertain if the intensity chosen during Bi_{SSI} is truly representative of the triathletes' Ironman cycle-race intensity. However, the final RPE measured during Bi_{SSI} of 15.0 (0.4) Borg units suggests that the athletes perceived this as a hard effort.

In conclusion, the present study has provided evidence to suggest that ultra-endurance triathletes perform the cycling phase of the ultra-endurance triathlon at a mean PO that is significantly below their $PO_{Th,vent}$ ($P < 0.05$). However, in line with previous findings, this study has shown that ultra-endurance triathletes cycle during the Ironman triathlon at a HR that is near $HR_{Th,vent}$. Further research is needed to examine pacing strategies and the determinants of fatigue during endurance and ultra-endurance exercise.

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References

Aunola S, Alanen E, Marniemi J, Rusko H (1990) The relation between cycling time to exhaustion and anaerobic threshold. Ergonomics 33:1027–1042

Barstow TJ, Jones AM, Nguyen PH, Casaburi R (1996) Influence of muscle fiber type and pedal frequency on oxygen uptake kinetics of heavy exercise. J Appl Physiol 81:1642–1650

Barstow TJ, Mole PA (1991) Linear and nonlinear characteristics of oxygen uptake kinetics during heavy exercise. J Appl Physiol 71:2099–2106

Borg GA (1982) Psychophysical bases of perceived exertion. Med Sci Sports Exerc 14:377–381

Brooks GA (1985) Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exerc 17:22–34

Coyle EF, Feltner ME, Kautz SA, Hamilton MT, Montain SJ, Baylor AM, Abraham LD, Petrek GW (1991) Physiological and biomechanical factors associated with elite endurance cycling performance. Med Sci Sports Exerc 23:93–107

Coyle EF, Montain SJ (1992) Carbohydrate and fluid ingestion during exercise: are there trade-offs? Med Sci Sports Exerc 24:671–678

Davis JA (1985) Anaerobic threshold: review of the concept and directions for future research. Med Sci Sports Exerc 17:6–21

Davis JM, Bailey SP, Woods JA, Galiano FJ, Hamilton MT, Bartoli WP (1992) Effects of carbohydrate feedings on plasma free tryptophan and branched-chain amino acids during prolonged cycling. Eur J Appl Physiol 65:513–519

De Vito G, Bernardi M, Sproviero E, Figura F (1995) Decrease of endurance performance during Olympic Triathlon. Int J Sports Med 16:24–28

Farrell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL (1979) Plasma lactate accumulation and distance running performance. Med Sci Sports 11:338–344

Frangolias DD, Rhodes EC (1996) Comparison of the lactate and ventilatory thresholds during prolonged work. Sports Med 22:38–53

Green HJ, Hughson RL, Orr GW, Ranney DA (1983) Anaerobic threshold, blood lactate, and muscle metabolites in progressive exercise. J Appl Physiol 54:1032–1038

Hill DW, Leiferman JA, Lynch NA, Dangelmaier BS, Burt SE (1998) Temporal specificity in adaptations to high-intensity exercise training. Med Sci Sports Exerc 30:450–455

Hopkins SR, McKenzie DC (1994) The laboratory assessment of endurance performance in cyclists. Can J Appl Physiol 19:266–274

Hopkins WG, Schabort EJ, Hawley JA (2001) Reliability of power in physical performance tests. Sports Med 31:211–34

Howell DC (1997) Statistical methods for psychology, 4th edn. Duxbury Press, Belmont, Calif.

Jones AM, Carter H, Doust JH (1999) A disproportionate increase in VO_2 coincident with lactate threshold during treadmill exercise. Med Sci Sports Exerc 31:1299–1306

Lambert MI, Mbambo ZH, St Clair Gibson A (1998) Heart rate during training and competition for long-distance running. J Sports Sci 16:S85–S90

Laursen PB, Rhodes EC (2001) Factors affecting performance in an ultraendurance triathlon. Sports Med 31:195–209

Laursen PB, Rhodes EC, Langill RH (2000) The effects of 3,000-m swimming on subsequent 3 h cycling performance: implications for ultraendurance triathletes. Eur J Appl Physiol 83:28–33

Laursen PB, Rhodes EC, Langill RH, Taunton JE, McKenzie DC (2002) The ventilatory response to progressive cycling, running, and running following 5 h cycling in triathletes. Respir Physiol (in press)

Loat CER, Rhodes EC (1996) Comparison of the lactate and ventilatory thresholds during prolonged work. Biol Sport 13:3–12

Noakes TD (2000) Physiological models to understand exercise fatigue and the adaptations that predict or enhance athletic performance. Scand J Med Sci Sports 10:123–145

Noakes TD, Peltonen JE, Rusko HK (2001) Evidence that a central governor regulates exercise performance during acute hypoxia and hyperoxia. J Exp Biol 204:3225–3234

O'Toole ML, Douglas PS (1995) Applied physiology of triathlon. Sports Med 19:251–267

O'Toole ML, Douglas PS, Hiller WD (1989) Lactate, oxygen uptake, and cycling performance in triathletes. Int J Sports Med 10:413–418

O'Toole ML, Douglas PS, Hiller WD (1998) Use of heart rate monitors by endurance athletes: lessons from triathletes. J Sports Med Phys Fitness 38:181–187

O'Toole ML, Hiller DB, Crosby LO, Douglas PS (1987a) The ultraendurance triathlete: a physiological profile. Med Sci Sports Exerc 19:45–50

O'Toole ML, Hiller WDB, Douglas PS, Pisarello JB, Mullen JL (1987b) Cardiovascular responses to prolonged cycling and running. Ann Sports Med 3:124–130

Rhodes EC, McKenzie DC (1984) Predicting Marathon time from anaerobic threshold measurements. Phys Sports Med 12:95–99

Roalstad M, Crosby L, O'Toole ML, Zigler A, Grotke G, Hiller WDB (1987) Heart rate monitoring during an ultraendurance event. Med Sci Sports Exerc 19:S71

Schabort EJ, Killian SC, St Clair Gibson A, Hawley JA, Noakes TD (2000) Prediction of triathlon race time from laboratory testing in national triathletes. Med Sci Sports Exerc 32:844–849

Selley EA, Kolbe T, Van Zyl CG, Noakes TD, Lambert MI (1995) Running intensity as determined by heart rate is the same in fast and slow runners in both the 10- and 21-km races. J Sports Sci 13:405–410

Sleivert GG, Wenger HA (1993) Physiological predictors of short-course triathlon performance. Med Sci Sports Exerc 25:871–876

Speedy DB, Noakes TD, Rogers IR, Thompson JM, Campbell RG, Kuttner JA, Boswell DR, Wright S, Hamlin M (1999) Hyponatremia in ultradistance triathletes. Med Sci Sports Exerc 31:809–815

St Clair Gibson A, Lambert ML, Noakes TD (2001a) Neural control of force output during maximal and submaximal exercise. Sports Med 31:637–650

St Clair Gibson A, Schabort EJ, Noakes TD (2001b) Reduced neuromuscular activity and force generation during prolonged cycling. Am J Physiol Regul Integr Comp Physiol 281:R187–R96

Takano N, Tamura N, Chaki K (1991) Exercise-entrained breathing and non-invasive determination of anaerobic threshold. Respir Physiol 86:381–392

Wasserman K (1984) The anaerobic threshold measurement to evaluate exercise performance. Am Rev Respir Dis 129:S35–S40

Weston AR, Myburgh KH, Lindsay FH, Dennis SC, Noakes TD, Hawley JA (1997) Skeletal muscle buffering capacity and endurance performance after high-intensity training by well-trained cyclists. Eur J Appl Physiol 75:7–13

Xu F, Rhodes EC (1999) Oxygen uptake kinetics during exercise. Sports Med 27:313–327

Zhou S, Robson SJ, King MJ, Davie AJ (1997) Correlations between short-course triathlon performance and physiological variables determined in laboratory cycle and treadmill tests. J Sports Med Phys Fitness 37:122–130