Review Article

Physiological requirements in triathlon

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INTRODUCTION

Exercise physiologists working with triathletes have to deal (1) with different exercise modes; (2) variations in swim, cycle and run training history between the athletes that in turn influence their training adaptations and physiological profiles; (3) different genders and finally (4) different triathlon distances (in this article, we shall focus only on Olympic distance OD vs. Long Distance LD).

'Traditional' viewpoint

Traditionally [1-4], endurance performance is thought to be mainly determined by the following factors: maximal oxygen consumption (VO2max); Lactate/ventilatory threshold (LT/VT) and Economy/efficiency (Figure 1) together with – depending on the distance and the authors –Anaerobic Capacity (AC) or critical Power (CP).

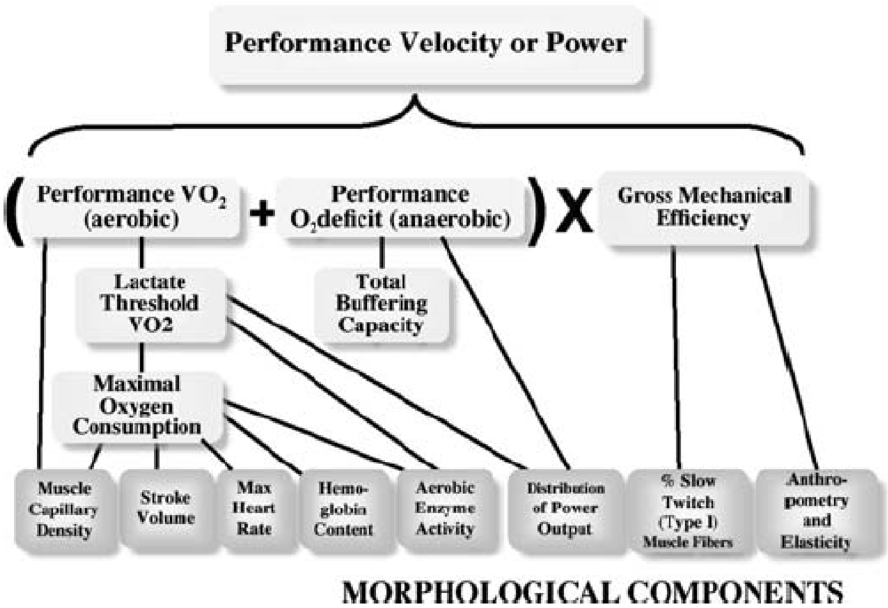

Figure 1. *Overall schematic of the multiple 'traditional' physiological factors that interact as determinants of performance velocity or power output [4].*

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It is of interest to note that only the two first of these factors (VO_2max and LT/VT) have been extensively investigated in triathletes.

"Performance $\dot{V}O_2$" (*i.e.* how long a given rate of aerobic and anaerobic metabolism can be sustained) is determined by the interaction between $\dot{V}O_2$max and lactate threshold (LT), whereas efficiency determines how much speed or power (*i.e.* "performance velocity") can be achieved for a given amount of energy consumption [4]. However, these physiological variables measured in either cycling and running may adapt indifferently as a consequence of cross training in cycling and running [5-16]; cross training being defined as 'combined alternative training modes within a sport specific regime'. It is also possible that the results of such physiological tests in cycling and running may be influenced by the athlete's original training background. By comparing physiological variables as maximal oxygen consumption ($\dot{V}O_2$max), anaerobic threshold (AT), heart rate, economy or delta efficiency measured in cycling and running in triathletes, we aimed to identify the effects of exercise mode on, and whether triathletes competing in OD vs LD events differ as regards, physiological profile.

'Contemporary' viewpoint

Recently [1], it has been suggested that "*these 'traditional' parameters are important because they determine the character of, and place constraints upon, the kinetics of VO_2 during exercise. … We suggest that only by appreciating how the 'traditional' parameters of physiological function interact with the kinetics of VO2 can the physiological determinants of athletic performance be truly understood".*

This 'contemporary' viewpoint [1] claims that the characteristics of the VO_2 kinetics [for a review; [17]]- that describe the time course of VO_2 at onset of exercise (or to a larger extent during any increase in intensity)- determine the 'intensity domains' (Figure 2) and therefore the rate of changes (accumulation / storage / utilisation) in the 'traditionally'-described limiting factors of performance (Figure 3).

Domain	Boundaries	$\dot{V}O_2$ kinetic responses	Endurance time	Likely fatigue mechanisms
Moderate	Upper: LT	Two components; steady state achieved within 3 min in healthy individuals	>4 h	Hyperthermia (in the heat), reduced central drive/ motivation ("central fatigue"), muscle damage (running)
Heavy	Lower: LT Upper: CP	Three components; slow component evident after primary phase; steady state delayed by 10–20 min; elevated $\dot{V}O_2$	Up to ~3–4 h	Glycogen depletion, hyperthermia
Severe	Lower: CP Upper: highest power that elicits $\dot{V}O_{2max}$ before fatigue	Two/three components; slow component evident that develops continuously if power below $\dot{V}O_{2max}$; no steady state; $\dot{V}O_{2max}$ attained if sustained	Up to ~30–45 min	Depletion of finite energy store represented by W' or the oxygen deficit and/or accumulation of fatiguing metabolites (e.g. H^+, $H_2PO_4^-$)
Extreme	Lower: highest power eliciting $\dot{V}O_{2max}$	Two components; no slow component evident; $\dot{V}O_{2max}$ not attained	<120 s	As for severe + excitation–contraction coupling failure

Note: LT = lactate threshold; CP = critical power.

***Figure 2**. The 'intensity domains' [1].*

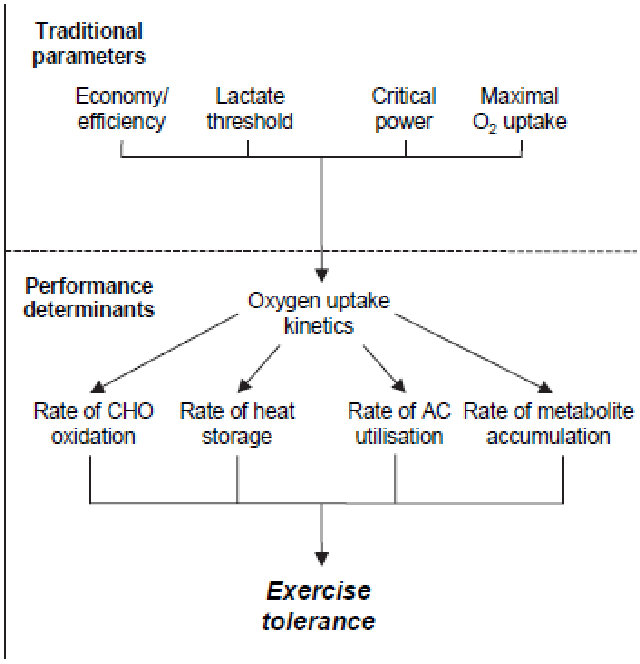


Figure 3*. The role of VO_2 kinetics in heavy- and severe-intensity exercise tolerance [1] (Key: CHO carbohydrate, AC anaerobic capacity).*

It is surprising that there are very few studies describing or comparing VO_2 kinetics in triathletes.

1. Training characteristics of LD vs OD triathletes

Given the different race intensity and durations of OD and LD racing, and the fact that athletes increasingly tend to specialise in one or the other competition, it is logical that significant training (and therefore, physiological) differences, should exist between the two groups. Surprisingly, however, little examination of the way that LD vs. OD triathletes train has been carried out. Table 1 (overleaf) summarises the results of the only comparative study that exists to date (Vleck et al., 2009, Vleck 2010).

Essentially, OD athletes spend less time per week than LD athletes doing 'long run' ($p<0.05$ for both genders) and 'long bike' sessions ($p<0.05$, for females only). The length of individual such sessions is also less in OD than LD athletes in ($p<0.05$). Squad OD athletes also do more speed work cycle and less long run sessions per week (both $p<0.05$). Less elite OD athletes do back to back cycle run training than LD athletes (p<,0.05).

***Table 1**. Training characteristics of British (1994) National Squad triathletes during a typical race training week without taper.*

		Elite male OD	Sub-elite male OD	Elite male IR	Elite OD female	Sub-elite OD female	Female IR elite
Number of sessions per week	Long bike	1.1 ± 1.3	1.2 ± 1.1	1.5 ±1.5	1.5 ± 0.6	1.4 ± 1.6	2.3 ± 1.3
	Hill rep bikes	0.3 ± 0.5*	0.2 ± 0.4	0.3 ± 0.5	1.2 ± 1.1*	0.6 ± 0.5	0.5 ± 1.0
	Speed work bike	1.5 ± 1.0	2.1 ± 1.0	1.5 ± 1.0	2.1 ± 1.0	1.0 ± 0.6	0.5 ± 0.6
	Other bike	1.1± 1.3	1.1± 1.1	1.5 ±1.5	0.5 ± 0.6	1.4 ± 1.6	2.3 ± 1.3
	Long run	0.7 ± 0.5	0.7 ± 0.5$^{\otimes}$	1.0 ± 0.7$^{\otimes}$	0.8 ± 0.5	0.7 ± 0.5	0.8 ± 0.5
	Hill rep run	0.3 ± 0.5	0.3 ± 0.4	0.3 ± 0.6	0.25 ± 0.5	0.0	0.5 ± 0.58
	Speed work run	1.2 ± 0.8	1.5 ± 1.2	1.1 ± 0.5	1.0 ± 0.0	1.6 ± 0.8	1.0 ± 0.0
	Other run	2.0 ± 2.0	2.2 ± 1.3	2.2 ± 1.7	1.0 ± 0.0	1.4 ± 0.8	1.5 ± 0.6
Hours per week	Long bike	3.2 ± 2.6	3.1 ± 2.7	4.7 ±1.8	2.45 ± 1.4$^{\bullet}$	2.25 ± 1.8	5.8 ± 1.7$^{\bullet}$
	Hill rep bike	0.3 ± 0.7	0.1 ± 0.4	0.8 ± 0.9	0.7 ± 0.8	0.0	0.0
	Speed work bike	1.2 ± 0.7	1.3 ± 1.0	1.1 ± 0.8	1.45 ± 1.0	5.95 ± 10.7	1.0 ± 0.8
	Other bike	1.6 ± 1.6	1.4 ± 1.7	2.4 ± 3.0	0.9 ± 0.9	1.5 ± 0.4	2.6 ± 1.0
	Long run	1.3 ± 1.0$^{\oplus}$	0.4 ± 0.6$^{\oplus}$	1.6 ± 0.7	0.7 ± 0.6	0.2 ± 0.3$^{\phi}$	2.2 ± 0.3$^{\phi}$
	Hill rep run	0.4 ± 0.5	0.2 ± 0.3	0.8 ± 0.9	0.2 ± 0.5	0.0	0.5 ± 0.6
	Speed work run	0.8 ± 0.6	1.0 ± 1.0	0.9 ± 0.7	0.8 ± 0.6	1.13 ± 1.0	0.87 ± 0.1
	Other run	1.2 ± 0.9	1.0 ± 1.3	0.5 ± 0.4^{x}	0.6 ± 0.6	1.5 ± 0.6	1.3 ± 0.6^{x}
Distance (km)	Long bike	105.0 ± 75.7	80.5 ± 52.5	52 ± 73.5	68.5 ± 29.3	86.2 ± 43.0	116.0 ± 31.8
	Hill rep bike	-	-	8.0 ± 11.3	11.8 ± 17.8	16.6 ± 19.3	0.0
	Speed work bike	49.5 ± 24.6	47.7 ± 33.3	28.0 ± 17.0	16.0 ± 17.0	29.0 ± 21.5	8.0 ± 13.9
	Other bike	54.1 ± 83.6	53.8 ± 78.2	0	36.9 ± 34.8	24.1 ± 33.2	24.3 ± 24.0
	Long run	16.8 ± 15.1	10.9 ± 11.5	12.0 ± 17.0	12.0 ± 7.0	14.9 ± 6.5	20.1 ± 6.4
	Hill rep run	5.6 ± 7.8°	2.5 ± 4.2	0.0°	2.5 ± 4.2	1.5 ± 4.2	1.0 ± 1.7
	Speed work run	6.5 ± 6.3	9.8 ± 8.1	8.3 ± 10.9	8.6 ± 9.1	7.7 ± 5.0	9.2 ± 6.0
	Other run	-	10.3 ± 7.1	24.6 ± 19.0	17.4 ± 15.5	4.6 ± 5.6	7.3 ± 4.8

Abbreviations: 'OD' Olympic distance, 'IR' Ironman distance
$^{\otimes}$, $^{\circ}$, $^{\bullet}$, $^{\times}$, $^{\phi}$ or $^{\oplus}$ significantly different value ($p<0.02$) from group marked with same symbol.
*, $^{+}$, $^{\clubsuit}$, or $^{\varnothing}$ significantly different value ($p<0.05$) from group marked with same symbol.

Data on weekly training volume in hours (Table 2) or mileage (Table 3), that are differentiated by competitive distance, ability level and or gender, are scarce. Retrospective studies investigating whether training content has increasingly diverged between OD and LD triathletes, since the 1980’s, would be of interest and potentially allow for better understanding of the extent to which the sport has changed over the past 30 years.

***Table 2**. Weekly training time (h).*

N	Sex	Ability	Dist.	Total/wk (h)	Swim/wk	Cycle/wk	Run/wk	References
21	M	Elite	Short	17.4	5.6	6.3	3.7	[16, 18-21]
20	F			13.4	3.7	6.6	3.0	[16, 21, 22]
46	M	Comp	Short	14.0	4.04	4.9	2.7	[23, 24]
								[20, 21, 25]
20	F			7.5	4.3	8.2	2.0	[21, 26]
60	M	Comp	Long	18.53	3.4 ± 1.4	8.3 ± 2.8		[27-32]
12		Elite		19.5 ± 7.6	6.1 ± 4.5	8.8 ± 4.5	3.9 ± 1.7	[20]
25	F	Comp		14.52	3.20 ± 1.78	5.70 ± 1.93		[27, 33]
7		Elite		18.5 ± 2.5	4.2 ± 0.6	3.8 ± 0.9	10.3 ± 2.3	[20, 21, 32]

***Table 3.** Triathlon training distance (km).*

N	Sex	Level	Dist.	Total /wk	Swim/wk	Cycle/wk	Run/wk	Reference(s)
45	M	E	Short	-	13.67	255.82	38.99	[16, 20, 21, 34-38]
121		C		19.1	12.0	201.1	43.0	[20, 36, 39-52]
20	F	E		187.8±69.4	12.2	180.4	54.6	[16, 21, 26]
33		C		194.4±43.2	9.5	74.32	27.78	[21, 26, 53]
22	M	E	Long	200.7±136.7	16.4	178.9	186.2	[20, 54]
97		C			10.2	326.8	58.7	[54-59]
7	F	E		196.9±67.3	11.0±3.0	148.3±61.7	37.5±112.3	[21]
26	F	C			9.8	353.4	72.4	[54, 57]
Key: M male F female E Elite C Competitive L low								

2. Maximal aerobic power and the anaerobic threshold in OD and LD triathletes

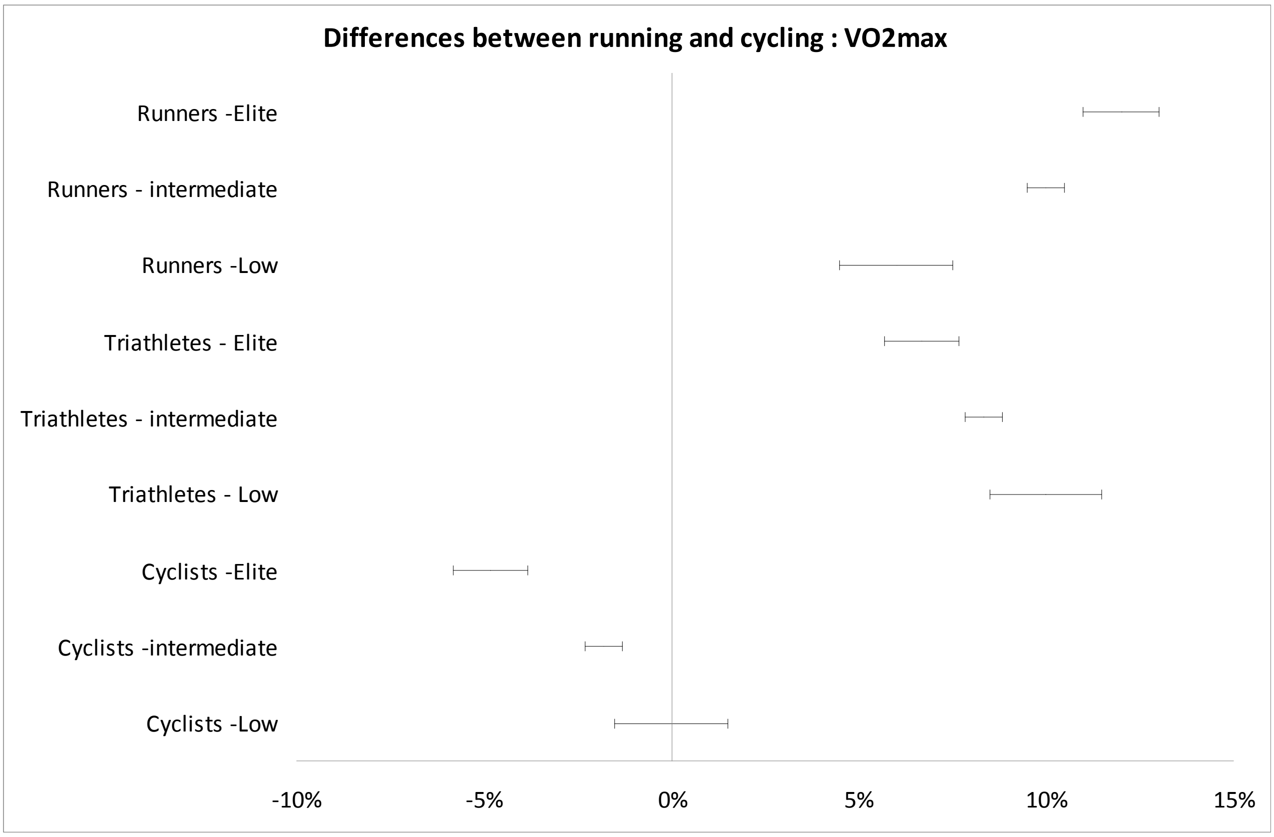
2.1 Maximal aerobic power

Table 4 shows the studies that have reported maximal oxygen uptake and peak work load or power for cycling and running in triathletes [11-13, 15, 49, 51, 60-95] .

Kohrt et al.[61] and O'Toole et al.[62] were among the first groups of researchers to compare $\dot{V}O_2$max of triathletes measured in both cycle ergometry and treadmill running. In 13 LD triathletes, they found that $\dot{V}O_2$max was significantly lower in cycle ergometry as compared with treadmill running (57.9 ± 5.7 vs. 60.5 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$). In contrast, O'Toole et al.[62] reported similar $\dot{V}O_2$max values for treadmill running and cycling. Therefore, the data were inconclusive as regards differences in $\dot{V}O_2$max between cycling and running in triathletes. Although said data were obtained during the 'early ages' of LD triathlon, however, they still appear valid.

Similarly, it seems that OD triathletes exhibit similar values for $\dot{V}O_2$max in cycling and running [12, 76, 80]. In another study, Miura et al.[87] examined two groups of triathletes whom they characterised as 'superior' or 'slower' level. They found no significant difference in $\dot{V}O_2$max in cycling and running in both groups. Therefore, any differences in $\dot{V}O_2$max between exercise modes may not be due to ability level. However, Schabort et al.[88] found $\dot{V}O_2$max to be significantly higher in treadmill running than cycle ergometry (68.9 ± 7.4 vs. 65.6 ± 6.3 $ml \cdot kg^{-1} \cdot min^{-1}$) in national level triathletes. Most studies have also shown that $\dot{V}O_2$max is similar (i.e. with less than a 7% difference, or approximately the 5 ml.min.kg of estimated methodological error that occurs during measurement of VO_2max) in cycling and running for triathletes over a wide range of competitive levels [12, 68, 75, 76, 80, 85].

A schema of the differences in VO_2max between cycling and running in triathletes is provided below (Figure 4). It emphasizes that the multi-sport training induces a profile that is intermediate to that of runners or cyclists.



2.2 Anaerobic threshold

Despite there is still controversy over the validity of the AT, a number of studies in triathletes have extended on initial studies by comparing both $\dot{V}O_2max$ and a measure of the AT in cycling and running in triathletes [12, 13, 76, 96, 97]. Table 5 shows the ventilatory or anaerobic threshold data in cycling and running in OD and LD triathletes [9, 12, 13, 39, 49, 51, 60, 66, 76, 80, 81, 87, 94, 96, 98-105].

Kohrt et al. [70] conducted a 6 to 8 month longitudinal investigation of 14 moderately trained LD triathletes. The researchers quantified $\dot{V}O_2max$ and the LT in both cycling and running. $\dot{V}O_2max$ remained relatively constant in both cycling and running until the latter stages of the training period, possibly reflecting an increase in training intensity at that time. However, $\dot{V}O_2max$ together with the LT in cycling was consistently lower than that obtained for treadmill running. This suggests that the subjects training background was more extensive in cycling than running. This study also indicates that the nature of training in either exercise mode may influence adaptation in cycling or running. In a more recent longitudinal study [106], taking over one season in trained OD triathletes, the relative stability of $\dot{V}O_2max$ and the larger change in VT under the influence of specific training was confirmed. However, Albrecht et al.[60] found no difference between the VT (expressed as % $\dot{V}O_2max$) obtained in cycling (78.8%) or running (79.3%). In accordance with this, Kreider[15] showed no significant difference in the VT in triathletes completing incremental tests in cycling and treadmill running.

Interestingly, these authors found that the exercise intensity sustained during the cycle and running stages of a OD triathlon was similar. In single sport endurance competitions it is generally thought that the AT reflects the ability to sustain a set percentage of maximum capacity [107]. Kreider's data[11], collected for a triathlon event, imply otherwise. Despite the VT of the athletes occurring at a different exercise intensity within isolated incremental running and cycling tests (90 vs. 85% of $\dot{V}O_2max$), the exercise intensity that they sustained during a race was similar for both exercise modes. However, De Vito et al.[102] showed the VT in running to be lower after prior cycle exercise in OD triathlon. These results and those reported by Zhou et al.[80] suggest that the cycle stage of a OD triathlon influences the ability to sustain a set percentage of maximal capacity during the subsequent running stage.

Miura et al.[87] also reported VT measured in cycling and running to be similar, in absolute terms, in two groups of triathletes who varied in OD triathlon race time. Schneider et al.[13] was able to confirm these findings and found that whilst $\dot{V}O_2max$ was significantly higher in running when compared with cycle exercise (75.4 ± 7.3 vs. 70.3 ± 6.0 $ml\cdot kg^{-1}\cdot min^{-1}$), the VT was not significantly different between cycling and running when expressed as an absolute $\dot{V}O_2$ value but did differ relative to $\dot{V}O_2max$ (66.8 ± 3.7 vs. 71.9 ± 6.6%).

2.3. Heart rate

In triathletes, the HR_{max} observed in cycling is often lower by 6-10 $b\cdot min^{-1}$ than that obtained during running[49, 70, 86, 108]. Longitudinal investigations have demonstrated HR_{max} to remain relatively stable over the course of a season[106], with higher values (~5 $b\cdot min^{-1}$) observed in running than in cycling[70]. In contrast, there is also evidence suggesting that HR_{max} is similar between cycling and running modes[61, 75, 80, 95, 107]. Although this appears to hold for males, differences were observed for this variable in females by some authors[63]. Schneider and Pollack[96], however, found no such significant differences between cycling and running HR_{max} in elite female triathletes.

The HR corresponding to the AT is used to prescribe submaximal exercise training loads [109, 110]. The data concerning triathletes indicate that the HR corresponding to certain inflection points associated with the AT is always higher in running than cycling, both when expressed in absolute terms and relative to HR_{max} [13, 49, 80, 86, 96, 108]. Schneider et al.[13] reported a significant difference in the HR corresponding to the VT in cycling and running (145.0 ± 9.0 vs. 156.0 ± 8.0) in 'highly trained' triathletes. This corresponded to 80.9 ± 3.4 vs. 85.4 ± 4.1% HR_{max}. In another study by the same research group and conducted on elite female triathletes [96], a higher HR was recorded at the VT in running than in cycling (164.7 ± 4.0 vs. 148.2 ± 3.4) and this difference was also evident when HR was expressed as a % of HR_{max} (87.3 ± 1.6 vs. 79.7 ± 1.5%). Similarly, Roecker et al.[108] found a difference of 20 b.min^{-1} between HR determined at the LT on cycling ergometer (149.9 ± 18.0 b.min^{-1}) and treadmill (169.6 ± 15.7 b.min^{-1}). However, recreational subjects (-22 b.min^{-1}) and cyclists (-14 b.min^{-1}) exhibited lower differences than triathletes and runners. Additionally, the differences were not influenced by gender.

There is some evidence that HR may not differ between cycling and running. Basset and Boulay [11] have reported that the relationship between HR and % $\dot{V}O_2$max did not differ when calculated either from a treadmill or from a cycle ergometer test. These authors showed also that HR was similar between running and cycle ergometer tests throughout the training year and concluded that triathletes could use a single mode of testing for prescribing their training HR in running and cycling throughout the year [95].

Zhou et al.[80] showed that the HR corresponding to the VT was significantly higher in running (174.6 ± 4.5) as compared with cycling (166.4 ± 7.6). However these authors found that the HR measured in a OD triathlon race was similar to the HR at the VT in cycling but much lower in running. Other studies have also shown a decrease in the HR_{max} and the HR corresponding to the VT during an incremental running test performed after submaximal cycling[48]. Hue et al.[49] have also demonstrated that the HR during a 10 km run after 40 km of cycling is higher when compared with the same run without cycling. Therefore, even though the HR corresponding to the AT or HR_{max} may be similar in running compared with cycling (in exercise tests performed in isolation), the HR corresponding to the AT determined from an incremental running test may be different to that observed in a race situation, especially in running. At elite level, due to the stochastic pace, there is no demand to control the exercise intensity for the run in OD triathlon via HR. Within LD triathlon, the potential use of HR for controlling the running pace might be of interest, at least at the beginning of the marathon. However, to our knowledge there is no published protocol for determining HR for this purpose. Furthermore, the effect of prior cycling on HR during running should be considered when prescribing HR during running training on its own.

2.4 Running economy

Running economy can be defined by the $\dot{V}O_2$ (in ml O_2.kg^{-1}.min^{-1}) of running at a certain speed, and is usually expressed by the energy cost (EC) of running a distance of one km (in ml.kg^{-1}.km^{-1}) calculated as $\dot{V}O_2$ divided by the velocity. EC has been reported in triathletes within both the conditions of isolated running and 'triathlon running' [14, 49, 66, 68, 105, 111-117]. It is generally reported that in trained OD triathletes, EC measured at the end of the event is higher by ~10% when compared to isolated run; *e.g.* 224 vs. 204 ml.kg^{-1}.km^{-1} [115]; 224 vs. 207 ml.kg^{-1}.km^{-1} [111]. It has also been reported that the extent of any change in EC subsequent to an exhaustive cycling bout is influenced by athlete performance level, event distance, gender, and age. The effect of a fatiguing cycling bout on the subsequent running energy cost was different between elite (-3.7 ± 4.8%, when compared to an isolated run) and middle-level (2.3 ± 4.6%) triathletes [116]. Elite LD triathletes had slightly (but not significantly) lower EC than OD triathletes (163.8 vs. 172.9 and 163.0 vs. 177.4 ml kg^{-1}.km^{-1} during an isolated and a 'triathlon' run, respectively) [14]. Surprisingly, no difference has been observed in EC between elite junior and senior triathletes, whether male or female, during an isolated run and a 'triathlon' run (173-185 ml.kg^{-1}.km^{-1}) [105]. However, the increase in EC subsequent to cycling was higher in juniors than in seniors in females (5.8 vs. -1.6%), but not in males (3.1 vs. 2.6%) [105].

The mechanisms underlying the deterioration in economy in the 'triathlon run' when compared to isolated run are various : both reported changes in the ventilatory pattern [86] leading to a higher $\dot{V}O_2$ of the respiratory muscles [116, 118], and neuromuscular alterations reducing the efficiency of the stretch-shortening-cycle [113, 116, 119] have been proposed. Some metabolic factors such as shift in circulating fluids, hypovolaemia and increase in body temperature have also been suggested [111, 114, 115]. Of interest are the studies of Hausswirth et al. [112-114], comparing EC at the end of OD triathlon and at the end of a marathon of similar duration: EC was more increased during marathon (+11.7%) than during OD triathlon (+3.2%) running when compared to an 45-min isolated run. The differences are due mainly to higher decrease in body weight related to fluid losses, a larger increase in core temperature during the long run and significant mechanical alterations during the long run when compared to the running part of a triathlon.

Interestingly, recent values of EC in World-level distance runners have been reported [120-122]: Jones [120] showed a continuous decrease in EC of Paula Radcliffe, the current world record holder for the Women's marathon between 1992 (~205 $ml.kg^{-1}.km^{-1}$) and 2003 (~175 $ml.kg^{-1}.km^{-1}$) corresponding to a 15% improvement whereas $\dot{V}O_2max$ (~70 $ml.kg^{-1}.min^{-1}$) and body mass (~54 kg) remained unchanged over the period. Jones reported also that her EC was more recently measured at 165 $ml.kg^{-1}.km^{-1}$. Billat et al.[123, 124] reported higher values in elite female Portuguese and French (196 ± 17 $ml.kg^{-1}.km^{-1}$) [124] or Kenyan (208 ± 17 $ml.kg^{-1}.km^{-1}$) [123] distance runners. Overall, this compares favourably with values obtained for elite female triathletes : Millet and Bentley [105] reported, for nine elite females (including one LD world champion, second at the Hawaii Ironman and five European medallists) an average value of 176.4 $ml.kg^{-1}.km^{-1}$, whereas the average $\dot{V}O_2max$ was 61.0 $ml.kg^{-1}.min^{-1}$ for a body mass of 60.3 kg.

In males, Lucia et al.[121, 122] reported a value of 150-153 $ml.kg^{-1}.km^{-1}$ in Zersenay Tadese, the current long cross-country and half-marathon World champion for a $\dot{V}O_2max$ of 83 $ml^{-1}.min^{-1}.kg^{-1}$. The EC of Tadese is lower (the lowest reported so far) than previously reported values in elite runners : 180 $ml.kg^{-1}.km^{-1}$ for Steve Scott[125]; 203-214 $ml.kg^{-1}.km^{-1}$ in elite French and Portuguese[124] or Kenyan[123] runners; ~190-192 $ml.kg^{-1}.km^{-1}$ in Elite East-African runners [121, 126]; ~211 $ml.kg^{-1}.km^{-1}$ in Elite Spanish runners[121]. So, similarly to females, with the exception of Tadese, running economy in male distance runners does not appear to be better than the ones reported in elite triathletes : 174± 9 and 164 ± 8 $ml.kg^{-1}.km^{-1}$ for OD and LD triathletes, respectively[14]. However further investigation with Elite LD triathletes is required to confirm these results. Overall, from these data, it appears that the main difference in running performance between elite runners and triathletes comes mainly from a higher body mass in triathletes (affecting proportional $\dot{V}O_2max$) rather from differences in running economy. Since mean lower leg thickness and calf mass have been shown to be related to running economy[127], one may speculate that the higher body mass in triathletes comes mainly from the upper body muscles more and – probably – from the higher skinfold thicknesses that are associated with swimming.

2.5. VO2 kinetics

As previously mentioned, in contrast to other endurance sports; i.e. running [128, 129] , cycling [129], rowing [130] or swimming [131] where VO_2 kinetics has been well-investigated, only a few studies report VO_2 kinetics parameters in triathletes.

Faster kinetics; i.e. smaller constant time of the primary phase (τ_1) , has been associated with improved fatigue tolerance and performance in cycling, running or rowing [1, 130]. Caputo et al. [132] compared trained triathletes, cyclists and runners on both running and cycling maximal exercises. τ_1 was similar between treadmill and cycle ergometer in runners (31.6 and 40.9 s); cyclists (28.5and 32.7 s) and triathletes (32.5 and 40.7 s). Despite the fact that these authors concluded that VO_2 kinetics was not dependent on the exercise mode and specificity of training as in previous studies [133], one may observe that the triathletes responses were similar to the ones of the runners, for whom the difference between cycling and running was larger than in cyclists.

It seems that in trained subject, acceleration of the VO2 adjustments at the onset of heavy exercise after endurance training is not always observed, in opposition to untrained subjects. For example, Millet et al. [134] did not report that in a group of already well-trained triathletes, training induces a faster constant time of the primary phase. However, they reported in the seven subjects with the lowest VO_2max (~64 mL·min·kg), that τ_1 decreased from 21 to 14 s.

Comparing the VO_2 kinetics parameters between OD and LD triathletes (in addition to running EC and cycling anaerobic capacity) appears as the first priority to characterize the training adaptations and better understanding the determinants of performance with a “modern” scientific perspective.

3. Injury Differences in OD and LD triathletes

It may, however, have implications for the incidence and or severity of overuse injury in these groups. In a preliminary retrospective study, Vleck et al [21] found the number of overuse injuries sustained over a five-year period did not differ between OD and LD triathletes. However, the proportions of OD and LD athletes who were affected by injury to particular anatomical sites did ($p<0.05$). For example, a greater proportion of OD than LD males sustained Achilles tendon injury ($p<0.05$). In addition more of the total number of overuse injuries that were sustained by OD athletes occurred to the lower back (17.9%), Achilles tendon (14.3%) and knees (14.2%), whilst most of the injuries that were reported by IR athletes were to the knees (44%), calf (20%), hamstrings (20%) and lower back (20%). Moreover, less OD athletes (16.7% vs. 36.8%, $p<0.05$) reported their injury to recur. Although OD sustained less running injuries than LD (1.6 ± 0.5 vs. 1.9 ± 0.3, $p<0.05$), more subsequently stopped running (41.7% vs. 15.8%), and for longer (33.5 ± 43.0 vs. 16.7 ± 16.6 days, $p<0.01$). In OD, the number of overuse injuries sustained inversely correlated with percentage training time, and number of sessions, doing bike hill repetitions ($r = -0.44$ and -0.39, respectively, both $p<0.05$). LD overuse injury number correlated with the amount of intensive sessions done ($r = 0.67$, $p<0.01$ and $r = 0.56$, $p<0.05$ for duration of 'speed' run and 'speed bike' sessions). It is important, therefore, that coaches note that the physiological and training differences between OD and LD triathletes may lead to their exhibiting differential risk for injury to specific anatomical sites.

Conclusion

After 30 years of scientific investigation, we can conclude that only the “traditional / old-fashion” physiological parameters (VO_2max, anaerobic threshold) have been measured and analysed at a large scale. Only few data are available for running EC or cycling efficiency in triathletes. Almost nothing has been published on anaerobic capacity in cycling or VO_2 kinetics. Very little is known regarding training content. Research regarding both the extent of, and the risk factors for, injury in LD and OD triathletes, is very much in its infancy.

The International Triathlon Union can be proactive in initiating a longitudinal assessment of elite triathletes. It will obviously help coaches and scientists. It might also complement the data collected in the “blood/biological passport” and be at the start of a “physiological passport”.

Table 4 . Studies that have assessed maximal oxygen uptake for cycling and running in OD and LD triathletes [135]

Reference	Sport	N	Level/ Details	Age (yrs)	Mass (kg)	Rel. VO_2max bike ($ml.kg^{-1}min^{-1}$)	Abs. $V0_2$max bike ($L.min^{-1}$)	Rel. VO_2max run ($ml.kg^{-1}min^{-1}$)	Abs $V0_2$max run ($L.min^{-1}$)
[60]	OD	9 M	Experienced			56.3		57.6	
[61]	LD	13 M	Competitive	29.5±4.8	69.8±5.6	57.9±5.6*		60.5±5.7*	
[62]	LD	8 M	Ser. amateur (SA)	30.5±8.8	74.7±10	66.7±10.1		68.8±10.4	5.1±0.9
		6 F	World-Class (WC)	31.3±5.6	60.3±4.6	61.6±7		65.9±8.1	3.9±0.4
		5 F	WC subgroup			67.0±7.7		61.0±8.5	
		1 F	SA subgroup			60.6		64.6	
		6M	SA subgroup			66.1±9.2		63.9±9.2	
		2 M	WC subgroup			77.0±10.0		75.1±10.0	
[63]	LD		Highly trained	30.5±8.8	74.7±10.0	66.7±10.1		68.8±10.4	
				31.3±5.6	58.8±5.7	64.0±8.9		68.1±9.4	
[64]	LD	8 F				56.9		61.0	
		10 M	Not clear			64.3		67.2	
[65]	LD	11 M	Top 200	31.4±5.9	74.5±7.6		4.7±0.3		4.8±0.3
[15]	OD	10 M	None given				4.6±0.5		4.9±0.8
[66]	LD	9 M				64.3±8.5		68.1±11.9	
[67]	OD	14 M	Competitive			43.6±8.1		49.7±7.5	
[68]	LD	11 M	Not clear	31.4±1.8	74.5±2.3	63.2±0.1	4.81	65.3±1.3	4.8±0.1
[69]	OD	4 M	'Elite'				4.7±0.4		4.8±0.4
[70]	LD	8 M, 6 F	(I, Feb.)	29.4±5.1	M 55.3-56.4 F 69.9-71.3	53.4±1.5*		57.4±1.4	
			(II, Feb+6-8 wks)			55.5±1.5*		57.89±1.5	
			(III,+6-8 wks)			54.2±1.5*		57.2±1.5	
			(IV, Sept., race)			56.0±1.3*		58.4±1.4	
[13]	OD	10 M	Highly trained	27.6±6.3	72±5.4	70.3±6*	5.1*	75.4±7.3*	5.4±0.6*
[71]	OD	10 M	Competitive			62.9±3.8		67.0±4.2	
[72]	LD	10 M	Not clear			60.8±1.4		61.6±1.1	
[73]	OD	7 F	Recreational			48.2±3.8	2.9±0.3	50.7±2.6	3.1±0.2
		16 M	Not clear			56.5±8.5		62.0±8.4	
[74]	OD	7 M	Competitive			60.5±6.2^{MW}		69.9±5.5^{MW}	
		7 M	Competitive			51.9±3.9^{HW}		55.6±4.1^{HW}	
[75]	OD	7 M		24±3	75±10	66.4±1		66.1±7.9	
[76]	OD	18 M		27.7±1.3	76.2±2.1	51.1±2		51.4±1.3	3.1±0.1
		7 F		28.3±2.3	59.3±2.1	60.1±1.5		63.7±1.6	4.8±0.1

Reference	Sport	N	Level/ Details	Age (yrs)	Mass (kg)	Rel. VO_2max bike (ml.kg-1min-1)	Abs. $V0_2max$ bike (L.min-1)	Rel. VO_2max run (ml.kg-1min-1)	Abs $V0_2max$ run (L.min-1)
[77]	OD	9 M				57.9±4.5		59.3±6.9	
[78]	OD	8 M				67.1±2.6		68.1±5.4	
[79]	OD	14 M				58.5±6.8		61.3±6.6	
[80]	OD	10 M	Amateur	27.4±5.7	78.4±8	61.3±10.1	4.75±0.5	63.3±8.9	4.9±0.2
[81]	OD	7 F				54.3±3.6		57.3±3.6	
		7 F				63.2±3.9		65.4±2.9	
[82]	OD	6 F	10 wks R	20.3±0.9	58.2±3.3		2.3±0.1*		2.6±0.1*#
		6 F	10 wks C	20.5±1.0	61.6±3.6		2.3±0.1*		2.5±0.1*
		6 F	10 wks C+R	21.3±0.6	62.4±3.0		2.5±0.2*		2.6±0.2#*
[83]	OD	5 M	Competitive			60.8±3.0		64.3±4.7	
[84]	OD	6 M					4.53±0.1		4.5±0.1
[85]	OD	17 M		26.5±8.2	62.8±5.1	61.1±8.1		63.8±8.1	
[49]	OD	7 M	Competitive	20.8± 2.9	69.7±4.5	65.4±4.2		62.1±6.3	
[86]	OD	9 M				70±4.8		71.7±4.9	
[87]	OD	8 M	Superior	27.3±6.8	65.4±5.8	67.8±6.1#		69.7±5.4#	
		8 M	Lower	26±10.3	60.8±3.2	54.9±3.8#		59.3±7.1#	
[11]	OD	4 M, 2 F		21.3±1.6	65.7±5.6	64.6±2.6*	4.2±0.6*	66.9±3.7*	4.4±0.4*
	C	6 M		24.3±7.5	72.5±3.7	71.2±3.9*	5.2±0.5*	75.3±3.8*	5.3±0.4*
	R	4 M, 2 F		21.0±2.4	64.8±13.8	61.7±5*	4.0±1.1*	68.4±4.1*	4.5±1.1*
	All	14 M, 2 F		22.2± 5	67.7±9.1	65.8±4.8*	4.4±0.1*	70.2±4.3*	4.7±0.8*
[12]	OD	29 M	Competitive	20.9±2.6	68±7.8	69.1±7.2	4.7	70.2±6.2	4.8±0.4
		6 M	Elite	21.8±2.4	69.9±7.3	75.9±5.2	5.3	78.5±3.6	5.5±0.3
[88]	OD	5 M	National Squad	23±4	72.1±4.7	69.9±4.5*	5.0±0.4	74.7±5.3*	5.3±0.5
		5 F		25±7	59.3±5.8	61.3±4.6	3.6±0.4	63.2±3.6	3.7±0.3
		5 M, 5 F				65.6±6.3	4.3±0.8	68.9±7.4	4.5±1
[89]	OD	8 M	Competitive			64.7±2.4		64.2±2.1	
			Elite Senior			75.7±2.3		76.3±3.2	
[90]	OD	12 M	Good level			70.7±3.8		61.0±6.2	
		12 M	Middle-level			67.7±6.4		56.9±5.5	
[91]	OD	13 M	University team			67.2±1.6		68.8±1.8	
[92]	OD	10 M				67.1±1.6		68.7±2.6	
[93]	OD	13 M	Competitive			67.2±1.6		68.8±1.8	
[94]	OD	8 M	University team	24.0±3.0	71.1±6.5	68.7±3.2		69.9±5.5	
[95]	OD	4 M, 4 F	Preparat. training	22±2	60.7±10	60.9±6.7		64.8±5.8	
			Specific training			61.9±6.4		66.1±6.9	
			Pre-competition			62.8±7.2		67.1±5.9	
[51]	OD	8 M		28.9±7.4	73.3±6.0	67.6±3.6	4.9±0.4	68.9±4.6	5.0±0.5

Table 5. Studies showing ventilatory / anaerobic threshold related data for cycling and running in triathletes [135]

Reference	Sport	Distance	Performance Level	N	VT VO_2_bike ($L.min^{-1}$)	VT VO_2 _run ($L.min^{-1}$)	VT VO_2_bike ($ml.kg^{-1}min^{-1}$)	VT VO_2_run ($ml.kg^{-1}min^{-1}$)	VT (% VO_2max_bike)	VT (% VO_2max_run)
[60]	T		Experienced	9 M			44.3	45.7		
[66]	T			10 M	3.9*	4.42*			85	90
[13]	T		Highly Trained	10 M	3.0±0.5*	3.9±0.3*	46.9±4.3	53.9±3.8	66.8±3.7	71.9±6.6
[96]	T		Highly trained	10 F	2.2±0.1	2.8±0.1	37.7±1.9	47.2±2	62.7±2.1*	74.0±2.0*
[76]	T			7 F					74.8±1.9	85.0±2.1
	T			18 M					81.4±1.3	85.0±1.3
[102]	T		Well trained	6 M		3.7±0.4		54.4± 4.4		79.5±3.6
						3.8±0.6		50±2.8		78.9±3.4
						3.7±0.2		59±2.8		80.9±6.2
[81]	T		Elite	7 M					71.8	86.2
[80]	T		Amateur	10 M	4.0±0.2*	4.5±0.2*	52.2±3.2*	57.7±2.7*	85±1.3*	91.1±1*
[49]	T		Competitive	7 M			42.5±6.5	46.4±6.3	65±9.9	74.7±10.1
[103]	T		Competitive						72.5±0.4	84.9±0.6
[87]	T		Superior	8 M			48.7±3.8#	50.9±4.8#		
	T		Lower	8 M			39.7±2.9#	40.4±4.8#		
[12]	T		All	29 M	3.0±0.6*	2.6±0.4*	45.1±8.2	46.7±4.1	65	66
	T		Elite	6 M	3.0±0.6	2.8±0.3	49±10.9	50.9±4.3	65	65
[94]	T			8 M					69.9±3.3	70.1±3.4
[39]	T		Well trained	9 M				67.0±3.6		
[104]	T		(Pre-comp)	7 M, 1 F	3.7±0.2#O		55.8±2.8#		88.9±0.2#	
			(Comp)	7 M, 1 F	3.7±0.2b		55.4±3.3		88.6±0.2#	
			(Post-comp)	7 M, 1 F	3.3±0.2#O		49±4.1c#		79±0.2	
[51]	T			8 M	(LT) 3.8±0.4*	(LT) 4.4±0.5*				

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