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Abstract:

This review focuses on strategic aspects which may affect performance during a long duration Olympic event: the Olympic distance Triathlon. Given the variety of races during Olympic games, Strategic aspects include as well improving technological features as energetical factors affecting the overall triathlon performance.. During the last decade, a lot of studies have attempted to identify factors reducing the metabolic load associated or not with the development of fatigue process by analysing the relationship between metabolic and biomechanical factors with exercise duration. To date, an actual consensus exists about the benefit to adopt a drafting position during the swimming or the cycling part of the triathlon. Other potential strategic factors such as the production of power output or the selection of cadence during the cycle leg or the running part are likely to affect the overall triathlon performance. Within this approach, pacing strategies are observed elite athletes who swim or cycle in a sheltered position inducing several changes of pace, intensity or stochastic shifts in the amplitude of the physiological responses. The analysis of these parameters appears to arouse some experimental and practical interests from researchers and coachers especially for long distance Olympic events.

Introduction

In human locomotion, theoretical best performance times is set by the product of the energy cost of the locomotion , i.e. the amount of metabolic energy spent to move over one unit of distance, and the maximal metabolic power, i.e. a function of maximal oxygen uptake (VO2max), and maximal anaerobic capacity [13,23]. Thus the energy cost of locomotion represents the efficiency of athletes and appears to contribute to the variation found in distance performance among athletes of homogeneous level. Endurance events such as triathlon or marathon running are known to modify biological constants of athletes and should have an influence on their efficiency. This has classically been shown to be important in sports performance, especially in events like long distance running, cycling or triathlon [13, 23, 36] In competition events, the energy cost for a given power output is dependent on both the energy (ATP) needed to overcome the external resistance and the energy used in the production of external energy (internal energy). Consequently, the energy cost of locomotion could be improved by reducing as well external energy and/or internal energy or both [24, 26]. In addition, many factors are known or hypothesised to influence the energy cost such as environmental conditions, athletes profile (trained or elite level), and metabolic modifications (e.g. training status, fatigue). Thus, strategic aspects of the race which may affect metabolic demand and performance during long duration events include as well energetical and biomechanical factors.

During the last decade, a lot of studies have attempted to identify these factors by analysing the relationship between metabolic and biomechanical factors with exercise duration during a specific Olympic event: the Olympic distance triathlon which takes approximately 2 hours to complete and presents the specificity to alternate three locomotion modes. [7, 29, 35].

Therefore, the purpose of this review, is to: (i) review strategies to improve efficiency of the athlete during locomotion; (ii) analyse the effects of these strategies on performance during an Olympic distance triathlon.

General point of view about Olympic Triathlon strategic aspects

The Olympic distance triathlon, involves successive swimming, cycling and running sessions, and begins with a swimming segment of 1500m, a 40km cycling leg and the race concludes with a 10km running leg. Given the variety of races during Olympic games or world cup races, these exercises are performed in various conditions of water temperature, road topography, surface and environmental conditions [20] . Therefore, recent studies have highlighted a possible discrepancy between factors affecting efficiency during competition and those classically identified during experimental settings in laboratory. One of the main differences is related to the stability of power output in laboratory studies when compared with pacing strategies used during races especially when competitive stakes are huge like during the Olympics games. The physiology of pacing during athletic events has only recently received full attention [3] . The pacing strategy is defined as the within-race distribution of power output, speed or voluntary adjustments induced by athletes during cycling and running (e.g. voluntary change in cadence or speed). Pacing has recently been hypothesized to be an important factor involved in the mechanisms of human fatigue and can be considered as a strategy to avoid catastrophic failure in any peripheral physiological system [50, 56]. According to this pacing strategies has been described as a nonlinear dynamic system leading to particular metabolic or neuromuscular fatigue when compared with constant intensity exercise [1, 3, 4, 9, 41]. Recent studies have tried to describe the power output profile during road cycling [4, 64] or during the cycle stage of the Beijing World cup test event (September 24st, 2006) of the future Olympic triathlon in China 2008 (Figure 1, Bernard *et al.*, unpublished data). These results have on the one hand highlighted the stochastic aspect of power output during an Olympic triathlon and on the other hand, the role of pacing strategies in fatigue appearance and decrease in efficiency. In recent studies focusing on factors affecting performance during an Olympic distance triathlon, the drafting position, power output production or cycling cadence selection have been reported to be the most common strategic factors used to explain changes in pacing strategies and performance over a swim-cycle-run combination.

Benefits of drafting in swimming : focus on variables conditioning positive effects

Drafting while swimming front crawl, *i.e.* swimming directly behind or at the side of another swimmer, is mainly used in triathlon races or open-water swims. Drafting allows the swimmer to

reduce the energy cost of swimming propulsion and hence gain time for swimming at maximal speed [18]. During swimming, hydrodynamic drag could be reduced when swimming in a drafting position. The effects of drafting during short swimming bouts have been widely studied in the recent literature [5, 17, 19]. The main factor of decreased body drag with drafting seems to be the depression made in the water by the lead swimmer [17]. This low pressure behind the lead swimmer decreases the pressure gradient from the front to the back of the following swimmer, hence facilitating his displacement.

In submaximal conditions, precisely at an intensity of 95% of maximal speed over a 549-m swim, Basset *et al.* [5] showed that drafting affected the metabolic responses to swimming. Oxygen uptake was reduced by 8 ± 12%, blood lactate concentration by 33 ± 17%, and the rate of perceived exertion by 21 ± 10%. The lower resistive body drag (passive drag) forces encountered by the swimmers at maximum speed are responsible for the observed metabolic change [18]. These forces were 13-26% lower than those for the lead swimmer, depending on the velocity of the triathletes (triathletes or swimmer). These authors showed specifically that swimming behind a leader resulted in an increase in swimming velocity (by 3.2%, *i.e.* 20-m benefits over a 400-m) and stroke length, and a reduction in blood lactate concentration and stroke frequency. They found that the gain of performance was related to the ability of the swimmer and his skinfold thickness, with faster and leaner swimmers achieving a greater gain. In this context, Chollet *et al.* [19] demonstrated that the performance increased from 1.34 $m.s^{-1}$ to 1.39 $m.s^{-1}$ when swimmers drafted the leader during a 400-m. Moreover, the authors concluded that drafting also contributes to stabilize the stroke parameters such as stroke frequency and stroke length during swimming.

The distance adopted by the drafting in swimming appears to be a consistent parameter which could be linked to overall swimming performance. Chatard *et al.* [17, 18] showed that the optimum drafting position was in the 0- to 50-cm range behind another swimmer, although a significant reduced metabolic response persisted at the 100- and 150-cm distances. This result confirmed the average 60-cm distance spontaneously adopted by drafters in high level triathlon (Millet *et al.* 2000). In triathlon, another parameter which is taken into consideration is the wearing of wet suit. Delextrat *et al.* [21] demonstrated that the significant effect of drafting previously reported in the scientific literature was observed even though subjects wear a wet suit. They showed a significant decrease in heart rate (7%) in drafting position during a 750-m where the "draftees" wear a wet suit. It could be concluded that during triathlon events, where subjects are wearing wet suits, drafting could either increase the reduction in metabolic load during swimming or develop an ability to swim faster. In addition, Mollendorf *et al.* [48] evidenced that it is possible that body suits that cover the torso and legs (*i.e.* like in triathlon) could reduce drag and then improve performance of swimmers. To conclude, several racing strategies has been developed by triathletes either to conserve energy for the swimming or for the cycling part of a triathlon.

Drafting in swimming and consequences on the subsequent cycling event

Research investigating the influence of swimming on subsequent cycling performance is somewhat limited [21, 38, 40]. However, despite the lack of experimental studies, recent reviews on triathlon determinants highlighted that the metabolic demand induced by swimming could have detrimental effects on subsequent cycling adaptations [7] . Recently, Delextrat *et al.* [21] have observed a significant decrease in cycling efficiency (17.5%) after a 750-m swim conducted at a sprint triathlon competition pace when compared with an isolated cycling bout. Actually, in an elite Olympic distance triathlon the strategy of drafting during the cycling part can influence the energy demands of this section as well as swimming and running strategies [7] . It is well known that the start and first third of the swim bout are a major determinant of the final race result [63] . These authors reported in an ITU world cup, the top performers in the overall triathlon were significantly faster in the first 400-500 m of the swim section. Moreover, the first 20-km of cycling has also been shown to influence to a large extent the overall results mostly linked to strategies employed during the race [7] . In a recent study, Delextrat *et al.* [21] demonstrated the decrease in metabolic load associated with swimming in a drafting position involved two main modifications in physiological parameters during subsequent cycling. Firstly, oxygen uptake kinetics, at the onset of cycling, were significantly slowed when the prior swimming bout was performed in a drafting position (slower time constant) compared with swimming alone . Secondly, a significantly higher cycling efficiency (+4.8%), measured at steady-state level, was observed in the drafting condition compared with the isolated swim. This improvement in cycling efficiency could be mainly accounted for by the lower swimming relative intensity involving a lower state of fatigue in the muscles of the lower limbs at the beginning of the subsequent cycling session (Figure 2).

Consequently, the authors suggested that the increase in cycling efficiency could lead to an improvement in the overall performance during a triathlon. In addition to this study, a more recent experiment conducted by Bentley *et al.* [6] compared the effects of drafting or a reduction of exercise intensity during swimming on the power output sustained during a subsequent cycle time trial. They found that the power output during a 20-min time trial in cycling was significantly lower after a 400-m all-out freestyle swimming at either 90% of this velocity or in a drafting situation conducted at the same velocity. The authors showed no significant difference in the power output during cycling performance after swimming at 90% or in a drafting position. Thus, they demonstrated that whilst swimming may affect cycling performance, drafting results in a similar performance response during cycling. This could have straight recommendations for training approach in triathlon and/or the strategy to adopt during world cup triathlon event. In the same context of World cup triathlon, Vleck *et al.* [63] showed that the position after the swim stage was better correlated to velocity measured at 222 m and 496 m. The overall finishing position in the Olympic distance triathlon was significantly correlated with the average swimming velocity (r=)-0.52) and the position after the swim stage (r=0.44). In addition, the authors recorded that the slower swimmers cycled significantly faster in the first 20 km of the cycle stage than the faster swimmers; this was reflected in the positions at the end of this stage with the slower swimmers effectively bridging the gap and could take benefits of a better sheltered position in the more numerous group of cyclists.

Benefits of drafting in cycling: focus on variables conditioning positive effects

During individual road cycling events, it is possible to very accurately predict performance given knowledge of the mass of the system (bicycle and rider), its aerodynamic characteristics, and the athlete’s physiological qualities [22, 51] . During multiple cyclist events riders have the opportunity to draft one another. In this context the magnitude of the drafting effect in cycling can be impressive. Jeukendrup *et al.* [34] showed an average power output of only 98 W during a stage of the Tour de France, some 152 W less than is estimated for a rider performing alone [34, 35] . McCole *et al.* [45] demonstrated that in drafting situation, a cyclist spare about 18% of oxygen uptake at 32 $km.h^{-1}$. and the benefit of drafting a single cyclist at

37 and 40 $km.h^{-1}$ was greater (27%) than at 32 $km.h^{-1}$. Recently, Edwards and Byrnes [25] hypothesized that leader drag area is an important determinant of the drafting effect in cycling. Therefore they indicated a strong mean effect of leader drag area, whether that effect is expressed in terms of the drag coefficient or power output. In addition, they found that the ratio between drag area of a leader and the drag area of a drafter is strongly correlated with the drafting effect.

Drafting in cycling and consequences on the subsequent run

Little is known about drafting in cycling and its influences on the following run during a triathlon. The first interesting finding was given by Hausswirth *et al.* [30] , indicating that drafting during the bike course of a triathlon (*i.e.* immediately after the swim leg) lowered both energy expenditure, heart rate and pulmonary ventilation values for a drafting distance of 0.2-0.5 m behind a lead cyclist. To our knowledge, drafting during the bike leg of a triathlon has not been scientifically documented, even if experiments focus on simulated outdoor triathlon and not triathlon achieved during a competition. Hausswirth *et al.* [30] demonstrated a global reduction oxygen uptake (-14%), heart rate (-7.5%) and pulmonary ventilation (-30.8%) for the drafted bike leg and for an average cycling speed of 39.5 $km.h^{-1}$. When we compared these data to the one found by McCole *et al.* [45] at a cycling speed of 40 km.h-1, the reduction in oxygen uptake was about –26%; the differences in saved oxygen uptake was explained by Hausswirth *et al.* [30] with the probably less efficiency at drafting during the initial phase (*i.e.* first 4-km) of the cycling section of the simulated outdoor triathlon, due to the residual negative effects of the swim stage. Because of the generalization of drafting in cycling during elite triathlon events (*i.e.* Olympic games) and the various race strategies now induced, it seems important that triathletes know the effects of pacing up with another cyclist in order to save energy for the consecutive run., More recently, Hausswirth *et al.* [31] investigated the physiological responses of riding alternatively or continuously behind another cyclist during a simulated indoor sprint distance triathlon. The authors showed a reduction by 16.5% in oxygen uptake and 11.4% in heart rate during the bike leg done continuously compared with the alternate cycling stage. In association, they recorded a better 5-km running performance after the continuous bike leg (+4.2%) compared with the run done after the alternate bike leg, indicating the practical interest to adopt a constant drafting position during the cycling leg the possible longer time. .

Drafting in running : should athletes take benefits ?

The first detailed study of the relation of oxygen uptake and speed in running was that of Sargeant [55] who solved the difficulties associated with the bag method by having his subjects run 120 yd holding their breath. Expired gas was collected for 40 min after running, and the resting supine oxygen intake was deducted from the total oxygen intake to give the oxygen uptake, and hence the energy requirement of the work. The results seemed to show that the oxygen uptake increased as the 3.8th power of velocity. Forty years after, Pugh [54] found that at a speed of 6 $m.s^{-1}$, 80% of the oxygen cost of meeting air resistance was eliminated by running close behind another runner. Unless some other adverse effect is present to cancel this advantage, an athlete should be able to exceed the speed corresponding to his maximal oxygen uptake by up to 7.5 x 0.80 = 6%, by running behind a pace-maker or a faster competitor. According to the relation of oxygen uptake and speed in track running found by Pugh (1970), the oxygen uptake corresponding to a speed of 6 $m.s^{-1}$ is 76 $mL.min^{-1}.kg^{-1}$ and the speed corresponding to a 6% greater oxygen uptake (i.e. 80.5 $mL.min^{-1}.kg^{-1}$) is 6.4 $m.s^{-1}$. This is equivalent of a reduction in time for a 400-m lap from 66.6 to 62.5 sec. Track experience, however, suggests that athletes cannot run close enough to gain as much as advantage as this. As presented in Fig. 3, the reduction in oxygen uptake achieved by running behind another runner at 6 $m.s^{-1}$ was 250 $mL.min^{-1}.kg^{-1}$; therefore, by running close behind another runner, oxygen uptake is 6.5% less than without shielding. Thus 80% of the energy cost of overcoming air resistance can be abolished by sheltering in running.

Actually, during the running stage of Elite triathlon races, the top 50% of athletes used to run at a speed of 5.30 $m.s^{-1}$ [63] which means closed to the speed where they could take benefits to be sheltered behind another runner. However, no triathlon runs are done on a track but only in field conditions, mostly on the road. Therefore, even the effect of shielding is well known to athletes and team managers, they have regarded it as a subjective effect. The observation that it has a physiological basis may enable them to use it with a greater tactical understanding than the previous running stages of Elite triathlon competitions.

Benefits of cadence choice during cycling : focus on variables conditioning positive effects

Additional cross-sectional studies have focused recently on the determination of pacing parameters that may be manipulated by triathletes during the cycle leg. In this case, the impact of cycling cadence during a cycle-run combination has received a great attention from researchers and coaches [7, 8, 28, 30, 61] . In a simulated triathlon, Hausswirth *et al.* [30] first demonstrated an indirect effect of cadence upon subsequent running performance. In this study, triathletes selected a cadence of 95 rpm during the drafting condition when compared to 89 rpm during the no-draft modality. It may be argued that the choice of a higher cadence (> 90 rpm) associated with a decrease in force applied to the crank and/or electromyographic (EMG) activity of lower muscle limb [58, 59] contributes to improve subsequent running performance. During constant-power laboratory testing, an apparent conflict is systematically observed between the energetically optimal cadence (EOC), i.e. the cadence at which $\dot{V}o_2$ is minimal, and the freely chosen cadence (FCC), i.e. the cadence that is spontaneously adopted during exercise [43, 44, 58]

. These investigators have shown that the EOC may vary from 55 to 65 rpm whereas FCC generally occurs between 80 and 95 rpm in endurance trained runners, cyclists or recreational subjects. This suggests that the reduction of aerobic demand is not a key determinant of preferred cadence selection during cycling exercise and several factors could be evoked. ,Therefore, it has been reported that the peak pedal force in cyclists reached a minimum value for cadences between 90 and 105 rpm, suggesting a pedalling skill to reduce pedal force at the highest cadences[58]. These authors have speculated that this pedaling skill induced a decrease in muscle stress and influenced the preferred cadence selection., The selection of a high cadence classically reported during isolated cycling exercise has been also linked to additional biomechanical and physiological parameters such as lower extremity net joint moments, i.e. calculated by computer modelling [44, 65], muscle synchronization [10] or improved heamodynamic adjustments [27].

During prolonged exercise, studies highlighted the magnitude of the exercise duration on the choice of cycling cadence in triathletes. Constant FCC values (81-83 rpm) have been reported during a 30-min cycle exercise, suggesting a relative stability of the movement pattern [11, 61] . Conversely, earlier investigations showed a decrease in FCC towards the most economical cadence after 1-h and 2-h cycling at a constant power output indicating the relationship between cadence selection and neuromuscular fatigue appearance [42, 62] (figure 4).

Cadence choice during cycling and consequences on the subsequent run

The effect of cadence on running performance has been recently investigated but limited data are available in this topic. During a laboratory-based investigation, Vercruyssen *et al.* [61] evidenced a relationship between the improvement of efficiency; i.e. decrease in energy cost, during running and the selection of prior cycling cadence at an intensity of 80-85 % $\dot{V}o_{2max}$. In this study, a reduction oxygen demand was observed during an overall cycle-run combination (30-min + 15-min) when triathletes select a cadence close to EOC (73 rpm). Conversely, the adoption of the FCC (81 rpm) or the theoretical mechanical optimal cadence (MOC, 90 rpm, [49]) during 30-min of cycling induced an increase in $\dot{V}o_2$ during the overall cycle-run combination. Several factors have been hypothesized to explain the observed differences between sessions, such as higher cycling metabolic load (i.e. high percentage of $\dot{V}o_{2max}$ sustained during the FCC and MOC conditions), changes in fibre recruitment patterns or variations in haemodynamic adjustments during the cycle-run sessions. These results may be in line with those reported recently by the same group of researchers about the relationship between cycling cadence and running performance [8]. These investigators have shown an effect of cadence on the capacity of triathletes to sustain an elevated fraction of $\dot{V}o_{2max}$ (F$\dot{V}o_{2max}$) during a 3000-m run performance. The highest F$\dot{V}o_{2max}$ values observed during running were found after cycling at 60 rpm (i.e. 92 % of $\dot{V}o_{2max}$) as compared to the other cycle-run combinations (i.e. 84-87 % of $\dot{V}o_{2max}$) where cadences were higher (80-100 rpm). Within this framework, Bernard *et al.* [8] indicated that the choice of a cadence close to 100-rpm was associated with an increased metabolic load during cycling and highlighted the poor strategy in terms of physiological benefits for triathletes to select high cadences before running. These findings suggest the possibility for triathletes to change the cadence before the cycle-run transition in order to optimise the first minutes of subsequent running and as result, the overall performance. In this context, Vercruyssen *et al.* [61] recently demonstrated that the change in cadence selection during the last part of cycling leg influences markedly subsequent running time to exhaustion. In this work, the decrease in cadence (close to 75 rpm and the energetically optimal cadence classically reported in literature) during the last ten minutes of cycling leg improves subsequent running time limit to exhaustion (894 s) when compared to the running time limit (624 s) where triathletes increased their cadence before the cycle-run transition. This improvement of running performance (*i.e.* running time limit) consecutive to the selection of low cadence may be linked to the reduced metabolic load reported during the final minutes of cycling leg compared with the selection of high cadence.

Furthermore, the results previously reported seem to be contradictory with anecdotal reports of competitive triathletes who prefer to select high pedalling cadence during the last minutes preceding the cycle-run transition [7] . Even if the selection of a low cadence appears to be linked to better metabolic responses in triathletes, future performance-based evaluations of different cycle-run combinations are needed to establish an optimal cycle-run strategy relating to the cycling cadence manipulation and to pacing strategy adpoted by triathletes

Pacing strategies adopted during a triathlon : swim-bike-run sections and its influences

Focusing on the relative importance of swimming in triathlon performance, few authors identified that the relationship between the $\dot{V}O_{2max}$ in swimming and overall triathlon performance did not exist [37] or is weaker than with $\dot{V}O_{2max}$ of the two others disciplines. Indeed, triathlon performance has been found to correlate to swimming (r=-0.62), cycling (r=-0.87) and running (r=-0.89) $\dot{V}O_{2max}$, but not to swimming economy (r=0.21; ns). The training in swimming for triathlon races did not differed so much from an isolated swimming race: but it was suggested that few factors influence swimming performance in triathlon as the propelling efficiency [37] , wetsuit advantage [15, 16] , and drating skills [19] which are specifics in swimming in triathlon. A recent study of Millet *et al.* [47] underlined - in comparing elite triathletes to elite swimmers that at highest swim velocities - triathletes increased their propulsive phases but less than the swimmers. They also increased their recovery phase while swimmers reduced it. Moreover, the strike length was lower for the triathletes than for the swimmers while there was no difference in the stroke rate. The authors concluded that the shorter stride length in triathletes would confirm that they have a lower propelling efficiency than swimmers [60] . Moreover, as wideley suggested, it seems that stride length is an appropriate and convenient criterion to evaluate technical improvement in triathletes.

Anecdotal reports from triathletes highlight the transition from cycling to running as the more tough of the two transitions in a triathlon event. Hence it is suggested that the format of the triathlon is advantageous toward athletes who can run well immediately after the cycling leg under fatigue conditions [66] , cycling leg which includes mostly a stochastic (*i.e.* variable) power output. However, the effects of metabolic responses and performance to constant *versus* variable-intensity bout on subsequent exercise have been examined especially during a cycle-cycle combination in trained cyclists [3, 52, 53]. For instance, Palmer *et al.* [52] demonstrated that following 150 min of steady-state riding, the subsequent 20-km time trial (TT) performance was improved, as compared to 150 min of stochastic exercise. However, it is important to note that this type of pacing strategy has been derived from cycling exercise conducted in laboratory settings or flat ourdoor sessions, without ant important changes in topography or wind conditions [2]. In a context of simulating cycling TT, Swain [57] predicted that the more a rider can vary power in parallel with changes in wind direction or gradient, the closer the ideal state of maintaining a constant speed is reached and, therefore, the greater the time saving. The author demonstrated that even modest (5% above or below a constant paced effort) variation in power would result in significant time savings. More recently, Atkinson et al. [4] investigated the acceptability of power variation during a cycling TT with simulated uphill and downhill sections. Results showed that finish times for the variable power trial (3370 s) was significantly faster than that for the constant power TT (3758 s). The authors concluded that some cyclists cannot fully adhere to a pacing strategy involving approximatively ±5% variation in mean power in parallel with gradient variation. Nevertheless, an important time saving can still result event if a variable pacing strategy is only partially adopted during a hilly TT, so that no additional physiological strain is incurred.

In the context of triathlon, the intensity in cycling can be constant when the cycling circuit is almost flat and when the competitors used to perform the cycling leg as an individual TT, speciffically when drafting is not allowed. In contrats, a constant power output profile is not recorded when environnemental conditions are modified because of hills, technical bike races or wind variations or when triathletes used to ride in a sheltered position (world cup events, olympic race), inducing very often changes in pace and intensity [1] .

For example, only few studies have examined the stride frequency and stride length during the running phase of an overground triathlon. Hausswirth et al. [32] showed the stride length to be reduced during a 30-min run occuring during a triathlon, from the 1st km-run to the end. However, the pace was reduced from 14.5 km.h^{-1} to 13;6 km.h^{-1}. Even the stride length was shorter during the cycle-run transition compared to a control run, the values were exactly the same for the two modalities of running at the end. A more recent study examined changes associated with individual muscle function when changing from cycling to running [33] ; they found that both level and duration of activation of several muscles (biceps femoris-BF, vastus lateralis-VL, vastus medialis-VM and rectus femoris-RF) were higher during the triathlon run compared to a control run. The authors explained the change from concentric muscle activation in cycling to stretch shortening muscle activation in running, may be due to a decreased ability of the VL and VM muscles to extend the knee in the flight phase of running, highlights a need for specific training for the cycle to run transition. In addition, transition to cycle-to-run induced a more forward leaning posture during the first km-run [29] . Therefore, specificity of training may allow appropriated coordination and active muscles to adapt efficiently to the transition between cycling and running without difficulties associated with the change in contraction type.

In adopting different running paces during the first km in a triathlon run, triathetes are able to achieved a better performance or not, dependently of the running speed itself. Accordingly, Hausswirth *et al.* [32] evidenced some interesting running strategies specifying that the choice of lower cadences, which result generally in lower stride rate and running speed values during the first kilometre [8] , could be a good strategy to improve running performance occuring during an olympic triathlon. In this study focusing on the role of different running strategies during an Olympic distance triathlon in elite triathletes, the first kilometre of running following cycling was performed at 5% faster, 5% slower or 10% slower than the average velocity recorded during the first kilometre of the isolated run. The remaining nine kilometres of each run was performed at a self-selected pace. Compared to the ten kilometres of the isolated run (IR) performance, results demonstrated that the best running strategy following cycling was the condition in which the first kilometre was performed 5 % slower (33min20s for the 10k-run), than the average speed of IR (33min48s for the 10k-run). This underline the need not to start so faster in running after cycling in order to keep the energy cost of running constant. Interestingly, a recent study [9] demonstrated that varying power output from 5% to 15% of the mean power during 20km cycling leg of a triathlon resulted in decreased performance in the subsequent 5 km run compared to a constant power output cycling strategy ; in constrast to studies focusing on cycling only [2, 57] , this study suggested in a context of a triathlon that the alteration in running performance could be due to greater neuromuscular fatigue induced by stochastic power in cycling. All results concerning the cycle-to-run transition could be applied in training programmes where coaches are paying attention to the so called “brick training”.

Conclusions

This review has outlined potential parameters that may be relevant in elite triathetes and more generally in cyclists or marathon runners to improve the overall Olympic performance. It has been shown that drafting position was the most prominent factor associated with successful performance. Other research have focused on the impact of power output production or cycling cadence during a cycle-run combination. Interestingly, cycling cadence choice appears to be also a important strategy to improve performance especially during the last running stage even if actually, contradictory results cause many difficulties to establish a preferential pedalling strategy prior to subsequent running event. Recent research suggested that the adaptation of triathletes must be considered as unique and relatively specific to the constraints activity (race profile, cycle-run transition, intensity and exercise duration)., Specifically for long duration Olympic events, topic concerning pacing strategies is relatively recent and requires to be extended to explain specific fatigue phenomenon appearance and the possibility to maintain or improve efficiency with exercise duration in such events.

References

1. Abbiss CR, Quod MJ, Martin DT, et al. Dynamic pacing strategies during the cycle phase of an Ironman triathlon. Med Science Sports Exer 2006; 38: 726-34.
2. Atkinson G., Brunskill A. Pacing strategies during a cycling time trial with simulated headwinds and tailwinds. Ergonomics 2000; 43:1449-1460
3. Atkinson G, Peacock O, St Clair Gibson A et al. Distribution of power output during cycling : impact and mechanisms. Sports Med. 2007a; 37:647-67.
4. Atkinson G., Peacock O., Law M. Acceptability of power variation during a simulated hilly time trial. Int J Sports Med 2007b; 28:157-163
5. Bassett DR, Flohr J, Duey WJ, et al.. Metabolic responses to drafting during front crawl swimming. Med Science Sports Exer 1991; 23: 744-7.
6. Bentley DJ, Libicz S, Jougla A, et al. The effects of exercise intensity or drafting during swimming on subsequent cycling performance in triathletes. J Sci Med Sport 2007; 10:234-43.
7. Bentley DJ, Millet GP, Vleck VE et al. Specific aspects of contempory triathlon. Sports Med 2002. 32:345-59.
8. Bernard T, Vercruyssen F, Grego F, et al. Effect of cycling cadence on subsequent 3-km running performance in well-trained triathletes. Br J Sports Med. 2003; 37:154-8.
9. Bernard T, Vercruyssen F, Mazure C et al. Constant versus variable-intensity during cycling: effects on subsequent running performance. Eur J Appl Physiol. 2007; 99: 103-11.
10. Bieuzen F, Lepers R, Vercruyssen F et al. Muscle activation during cycling at different cadences: Effect of maximal strength capacity. J Electromyogr Kinesiol 2006 20 112-23.
11. Brisswalter J, Hausswirth C., Smith D et al. Energetically optimal cadence versus freely-chosen cadence during cycling: effect of exercise duration. Int J Sports Med *2000;* 20: 1-5.
12. Broker JP, Kyle CR, Burke ER. Racing cyclist power requirements in the 4000-m individual and team pursuits. Med Sci Sports Exerc 1999; **31**:1677-85.
13. Capelli C, Schena F, Zamparo P et al. Energetics of best performances in track cycling. Med Science Sports Exer 1998; 30 : 614-24.
14. Capelli C. Physiological determinants of best performances in human locomotion. Eur J Appl Physiol. 1999; **80** :298-307.

15. Chatard JC, Senegas X, Selles M, Dreano P, Geyssant A. wet suit effect : a comparison between competitive swimmers and triathletes. Med Sci Sports exer 1995;27:580-586
16. Chatard JC, Millet GP Effects of wetsuit use in swimming events. Sports Med 1996; 22 **:** 70-5.
17. Chatard JC, Wilson B Drafting distance in swimming. Med Science Sports Exer 2003*;* 35: 1176-81.
18. Chatard, JC, Chollet D, Millet GP Performance and drag during drafting swimming in highly trained triathletes. Med Science Sports Exer 1998*;* 30: 1276-80.
19. Chollet D, Hue O, Auclair F et al. The effects of drafting on stroking variations during swimming in elite male triathletes. Eur J Appl Physiol 2000; 82:413-7.
20. Dallam GM, Jonas S Miller TK. Medical considerations in triathlon competition: recommendations for triathlon organisers, competitors and coaches. Sports Med. 2005; 35 :143-61.
21. Delextrat A, Tricot V, Bernard T et al. Drafting during swimming improves efficiency during subsequent cycling. Med Sci Sports Exer 2003*;* 35, 1612-9
22. di Prampero PE Cycling on earth, in space, on the moon. Eur J Appl Physiol 2000 ; 82, 345-60.
23. di Prampero PE. Factors limiting maximal performance in humans. Eur J Appl Physiol.2003; 90 :420-9.
24. di Prampero PE. The energy cost of human locomotion on land and in water. Int J Sports Med. 1986; 7: 55-72.
25. Edwards AG, Byrnes WC Aerodynamics characteristics as determinants of the drafting effect in cycling. Med Sci Sports Exerc 2007; 39:170-6.
26. Formenti F Minetti AE. Human locomotion on ice: the evolution of ice-skating energetics through history. J Exp Biol. 2007; 210 : 1825-33.
27. Gotshall RW, Bauer TA Fahmer SL Cycling cadence alters exercise hemodynamics. Int J Sports Med, 1996; 17: 17-21.
28. Gottshall JS Palmer BM The acute effects of prior cycling cadence on running performance and kinematics. Med Science Sports Exer, 2002; 34: 1518-22.
29. Hausswirth C Lehenaff D. Physiological demands of running during long distance runs and triathlons. Sports Med. 2001; 31: 679-89.

30. Hausswirth C, Lehénaff D, Dreano P et al. Effects of cycling alone or in a sheltered position on subsequent running performance during a triathlon. Med. Sci. Sports Exerc. 1999; 31:599-604.
31. Hausswirth C, Vallier JM, Lehénaff D et al. Effect of two drafting modalities in cycling on running performance. Med Sci Sports Exerc 2001; 33:385-90.
32. Hausswirth C, Bernard T, Vallier JM et al. Effect of different running strategies on running performance in Olympic distance Triathlon.; Proceedings of the 7th annual congress of the ECSS, Athens 2002, p183.
33. Heiden T., Burnett A. The effect of cycling on muscle activation in the running leg of an Olympic distance Triathlon. Sports Biomechanics 2003; 2:35-49
34. Jeukendrup AE, Craig NP, Hawley JA The bioenergetics of world class cycling. J Sci Med Sport 2000; 3:414-33.
35. Jeukendrup AE, Jentjens RL Moseley L. Nutritional considerations in triathlon. Sports Med. 2005; 35:163-81
36. Jones JH Lindstedt SL. Limits to maximal performance. Annu Rev Physiol. 1993; 55:547-69.
37. Kohrt WM, Morgan DW, Bates B, Skinner JS. Physiological responses of triathletes to maximal swimming, cycling and running. Med Sci Sports Exer 1987; 19:51-55
38. Kreider RB, Cundiff DJ, Hammet JB et al.. Effects of cycling on running performance in triathletes. Annals of Sports Med 1988; 3: 220-5.
39. Kyle, CR Reduction of wind resistance and power output of racing cyclists and runners travelling in groups. Ergonomics 1979; 22**:** 387-97.
40. Laursen PB, Rhodes EC, Langill RH The effects of 3000-m swimming on subsequent 3-h cycling performance: implications for ultraendurance triathletes. Eur J Appl Physiol 2000; 83: 28-33.
41. Lepers R, Theurel J, Hausswirth C et al. Neuromuscular fatigue following constant versus variable-intensity endurance cycling in triathletes. J Sci Med Sport. 2007; 9: 125-36.
42. Lepers,, Hausswirth C, Maffiuletti NA et al.. Evidence of neuromuscular fatigue after prolonged cycling exercise. Med Science Sports Exer 2000*;* 32: 1880-6.
43. Lucia A, Hoyos J, Chicharro JL Preferred pedalling cadence in professional cycling. Med Science Sports Exer 2001; 33: 1361-6.
44. Marsh, A.P, Martin PE Effect of cycling experience, aerobic power, and power output on preferred and most economical cycling cadences. Med Science Sports Exer 1997*;*

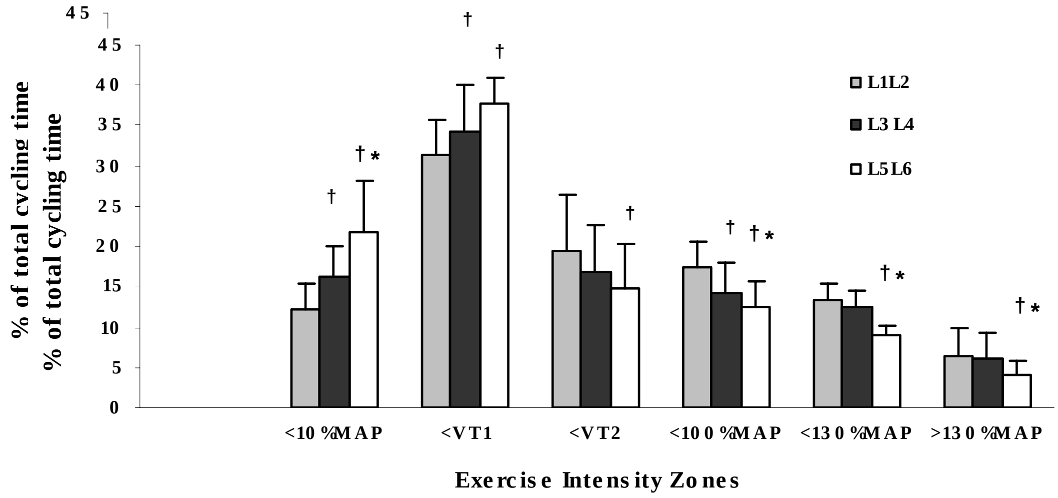
29: 1225-1232.

45. McCole SD, Claney K, Conte JC Et al. Energy expenditure during bicycling. J Appl Physiol 1990; 68:748-53.
46. Millet GP, Chollet D, Chalies S. Et al. . Coordination in front crawl in elite triathletes and elite swimmers. Int J sports med 2002; 23:99-104
47. Millet GP, Chollet D, Chatard JC Effects of drafting behind a two- or a six-beat kick swimmer in elite female triathletes. Eur J Appl Physiol 2000; 82: 465-71.
48. Mollendorf JC, TERMIN II AC, Oppenheim E, Pendergast DR. Effect of swim suit design on passive drag. Med Sci Sports Exer 2004; 36: 1029-1035
49. Neptune RR Herzog W The association between negative muscle work and pedaling rate. J Biomech 1999; 32: 1021-6.
50. Noakes TD, St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. Br J Sports Med 2005; 39:120-4.
51. Olds T Modelling human locomotion: applications to cycling. *Sports Med* 2001; 31:497-509.
52. Palmer GS, Noakes T, Hawley JA. Effects of steady-state versus stochastic exercise on subsequent cycling performance. Med Sci Sports Exer 1997; 29:684-687
53. Palmer GS, Borghouts LB, Noakes T, Hawley JA. Metabolic and performance responses to constant-load vs. Variable-intensity exercise in trained cyclists. J Appl Physiol 1999; 87:1186-1196
54. Pugh LG Oxygen intake in track and treadmill running with observations on the effect of air resistance. J Physiol 1970; 207, 823-35.
55. Sargent RM The relation between oxygen requirement and speed in running. Proc R Soc 1926; 100:10-22.
56. St Clair Gibson A, Lambert EV, Rauch LH, Tucker R, Baden DA, Foster C, Noakes TD. The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. Sports Med. 2006;36 :705-22.
57. Swain DP. A model for optimizing cycling performance by varying power on hills and in wind. Med Sci Sports Exer 1997; 29:1104-1108
58. Takaishi T, Ishida K, Katayama K Et al. Effect of cycling experience and pedal cadence on the near-infrared spectroscopy parameters. Med Science Sports Exer 2002 ; 34: 2062-71.
59. Takaishi, T, Yasuda Y, Ono T et al. Optimal pedaling rate estimated from

neuromuscular fatigue for cyclists. Med Science Sports Exer 1996; 28: 1492-7.

60. Toussaint HM. Differences in propelling efficiency between competitive and triathlon swimmers. Med Sci Sports Exerc 1990; 22:409-415
61. Vercruyssen F, Brisswalter J, Hausswirth C Influence of cycling cadence on subsequent running performance in triathletes. Med Science Sports Exer 2002; 34: 530-6.
62. Vercruyssen F, Hausswirth C, Smith D. et al. Effect of exercise duration on optimal pedaling rate choice in triathletes. Can J Appl Physiol 2001, 26: 44-54.
63. Vleck V, Bürgi A, Bentley DJ The consequences of swim, cycle, and run performance on overall result in elite Olympic distance triathlon. Int J Sports Med 2006; 27:43-8.
64. Vogt S, Heinrich L, Schumacher YO et al. Power output during stage racing in professional road cycling. Med Science Sports Exer 2006*;* 38 :147-51.
65. Widrick JJ, Freedson PS Hamill J Effect of internal work on the calculation of optimal pedaling rates. Med Science Sports Exer 1992*;* 24: 376-82.
66. Williams KR. Conquering rubbery legs off the bike (Part one) 2000. Triathlon and multisport; 3:16-17

Figure 1 Percentage of total cycling time to the exercise intensity zones during each section of the Olympic Triathlon distance world cup in Beijing (September 24st, 2006).

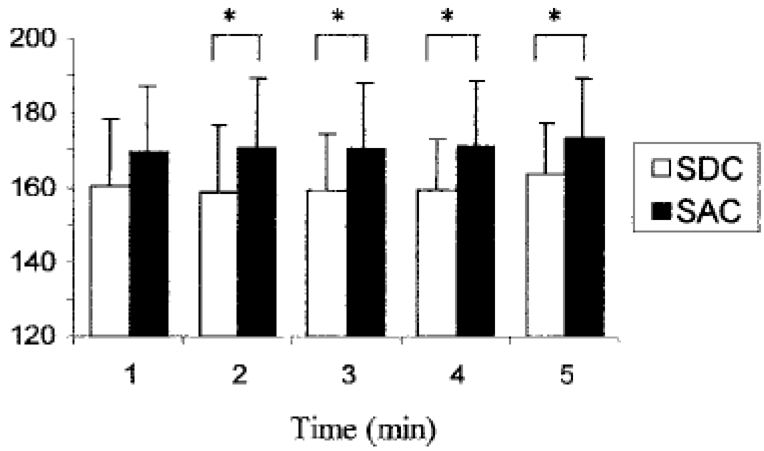


L1, L2, L3, L4, L5, L6 : cycling laps; VT : Ventilatory threshold, MAP : maximal aerobic power.

Mean ±SD. †significantly different from L1L2. *significantly different from L3L4. *P < 0,05*

Figure 2 Changes in Heart Rate during the last 5 min of the two swimming trials (SAC=alone, SDC=with drafting).

Heart rate (beats.min^{-1})



*** Significantly different between SDC and SAC trials, P<0.05 (adapted from Delextrat *et al.* [21]).**

Figure 3. O_2 intake and the square of wind velocity for subjects running at 4.46 m.s-1 against varying wind velocities alone on the treadmill and behind another runner (from Pugh, [54]).

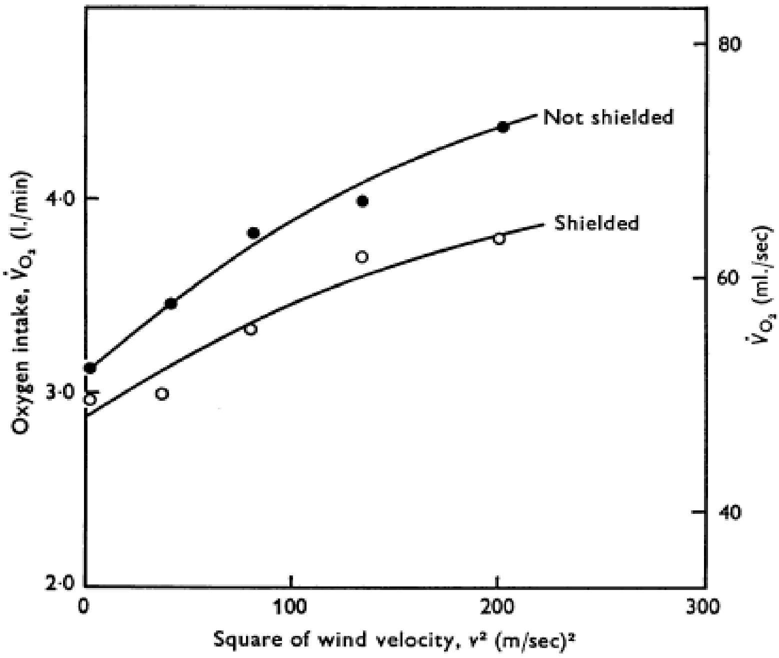


Figure 4. Variations in FCC with exercise duration in trained triathletes (Brisswalter et al., [11] (1); Lepers et al., [42] (2) and Vercruyssen et al., [62] (3), [63] (4)). This indicates a significant decrease in Freely Chosen Cadence (FCC) values with increasing exercise duration towards lower cycling cadences.