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SWIMMING, RUNNING, CYCLING AND TRIATHLON

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Summary
This chapter covers performance in cyclic sports activities, specifically swimming, running, cycling and triathlon, and the relevant performance indicators in each sport. Different approaches to monitoring performance in each sport are covered, as well as how coaches and athletes can use scientific evidence within coaching practice. Hence, the challenges of different strokes in swimming, the transitions in triathlon and different types of tactics at different distances in running and in cycling will be addressed during this chapter.

Introduction
Enhancing performance is the main goal for athletes, coaches, performance directors and researchers. Indeed, sports performance research has helped them to understand factors that determine athlete performance and to address several concerns regarding how one can control and evaluate these factors. The success of a training program is largely dependent upon satisfying the performance aims associated with it. Therefore, the evaluation and control of the training process can be used to: (i) try to predict future performance; (ii) identify athletes’ weaknesses; (iii) measure improvements; (iv) place the athlete in an appropriate training group and with appropriate training tasks; and (v) motivate the athlete (Marinho et al., 2009a).

This chapter presents a background to sports performance and to different approaches to monitoring performance, considering the role of performance indicators in individual, closed and cyclic sports. The authors will focus on underlying similar characteristics between swimming, running, cycling and triathlon, but will also identify differences between each sport that can influence performance. Practical implications for sports performance that can help athletes and coaches enhance performance will also be covered. In fact, how coaches and athletes can use scientific evidence in their daily activity, using coach-friendly language, will be reinforced within this book chapter.
In sports such as swimming, running, cycling and triathlon, the performance is mainly dependent on the interaction between several factors. Biomechanical and energetic factors are regularly considered to be the most important for performance (Barbosa et al., 2010a; Leirdal and Ettema, 2011). Biomechanics comprises kinematics, kinetics, neuromuscular analysis, biological maturation and anthropometric characteristics. Energetic variables comprise variables related to aerobic and anaerobic performance, cardio-respiratory profile, energy cost and efficiency (Barbosa et al., 2011; Costa et al., 2011). However, biomechanical and physiological factors are influenced by domains such as genetics, motor control and anthropometrics (Figure 35.1).

A large part of the research dedicated to competitive sports aims to identify variables that determine performance. This can be considered as an exploratory research trend. The aim of exploratory research is to identify which of several biomechanical and physiological variables are associated with or related to performance. This type of research has been developed based on: (i) applying exploratory regression models; (ii) comparing cohort groups; and (iii) implementing neural network procedures (Barbosa et al., 2010b).

One possibility is to develop statistical models to identify the best predictors of athlete performance (González-Badillo and Marques, 2010; Young et al., 2002). Another option is to compare cohort groups using mean values or analyzing the variation of some selected biomechanical and physiological variables between athletes of different competitive levels. For example, one can compare expert versus non-expert athletes (Baker et al., 2005; Seifert et al., 2007), national-level versus international/elite-level athletes (Hanon et al., 2011; Jesus et al., 2011) or the performances of World Championship and Olympic Games finalists versus non-finalists (Bourgois et al., 2000; Cappaert et al., 1996). Artificial neural networks are a recent approach to solving complex problems, and attempts have been made to predict sports performance using them (Hahn, 2006; Perl, 2004). Neural networks have also been used in talent identification processes, helping to make judgments about future performance levels based on the present individual skills and abilities. This is in contrast to contemporary cybernetic approaches to sports sciences where athletes are viewed as closed circuits and, thereby, an incoming training stimulus drives an equivalent outcome response represented as improved performance (Shestakov, 2005; Silva et al., 2007).

More recently, confirmatory data analysis has become a topic of interest for sports scientists. Such research designs aim to understand the relationships between the variables identified in previous studies and to model the links between them and performance (Barbosa et al., 2010a). This approach consists of a mathematical model for testing and estimating causal
relationships using both statistical data and qualitative causal assumptions, previously hypothesized by researchers, that need to be confirmed or otherwise.

This procedure not only identifies variables, but also indicates the types of interactions between them (Barbosa et al., 2010b). Structural equation modeling analyses the hypothetical relationships between several biomechanical and energetic variables and sports performance and evaluates the resulting model’s goodness-of-fit. Although this approach is used on a regular basis in sports psychology (Haney and Long, 1995; Spreitzer and Snyder, 1976), it is not so popular regarding energetics and biomechanical influence on sports performance; this is the case in swimming, running, cycling and triathlon. However, some attempts have been made to apply this procedure in these sports (Barbosa et al., 2010a; Morais et al., in press).

**Swimming**

**Energetics of swimming**

*Aerobic and anaerobic profile*

Swimming performance has been related to maximal total energy release and energy cost (Barbosa et al., 2006; Zamparo, 2006). Indeed, Wakayoshi et al. (1995) reported that energy expenditure correlated negatively with swimming performance. Moreover, considering energetic variables, swimming performance is dependent on aerobic and anaerobic parameters (Laffite et al., 2004). Several authors have reported that maximal oxygen uptake ($\text{V}O_{2\max}$) and lactate threshold were considered good swimming performance predictors (Rodriguez and Mader, 2003; van Handel et al., 1988). Additionally, some authors have reported the analysis of the accumulated oxygen deficit or peak post-exercise blood lactate and the subsequent anaerobic contribution to total energy expenditure for swimming performances (Figueiredo et al., 2011; Reis et al., 2010; Troup, 1992). Hence, physiological profile is one of the most relevant factors to enhance swimming performance.

In swimming, the contribution of the aerobic and anaerobic energy sources to total energy expenditure was shown to be independent of swimming technique, gender and skill (Zamparo et al., 2010). This contribution depends mostly on the duration of the race event (Capelli et al., 1998). At 45.7, 91.4 and 182.9 m (i.e. 50, 100 and 200 yards), Capelli et al. (1998) found that the aerobic component had a contribution to total energy expenditure of 15.3, 33.3 and 61.5 percent, respectively, for the front crawl stroke, 17.4, 36.4 and 59.2 percent, respectively, for the backstroke, 27.1, 46.5 and 67.9 percent, respectively, for the breaststroke and 16.9, 33.3 and 61.1 percent, respectively, for the butterfly. Capelli et al. (1998) also reported that the anaerobic alactic system contributed 20–25 percent (50 yards), 18–20 percent (100 yards) and 10–13 percent (200 yards) of the total energy for swimming different distances. These authors highlighted the important role of the anaerobic component to short-distance events (50 m and 100 m) and the major role of the aerobic component to events lasting at least two minutes (200 m). More recently, Figueiredo et al. (2011) reported a mean contribution of 65.9 ± 1.57 percent of aerobic sources during a 200 m front crawl test, which is similar to the 65 percent found by Ogita (2006) for a 2–3 min bout. Moreover, for the 400 m event, Rodriguez and Mader (2003), Laffite et al. (2004) and Reis et al. (2010) reported an aerobic contribution of 83.2, 81.1 and 95 percent, respectively. Some differences in the percentage contributions reported in the above-mentioned studies have to be attributed to the athlete samples used and their performance levels, but also to the methods used to estimate each of the energy components, particularly the alactic anaerobic one (Figueiredo et al., 2011). Although, as has been indicated by Gastin
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(2001), the methods by which energy release is determined have a significant influence on the relative contribution of the energy systems during periods of maximal exercise, these data seem to be relevant for swimming coaches when preparing training protocols. The relative contribution of each energy system to overall energy of different events can be used to focus special care on different training sessions (Marinho et al., 2006).

Biomechanics of swimming

Kinematics

Swimming velocity can be described by its independent variables: stroke length and stroke rate. Increases or decreases in swimming velocity are determined by combined increases or decreases in stroke rate and stroke length, respectively (Craig et al., 1985; Kjendlie et al., 2006; Toussaint et al., 2006). Stroke length is defined as being the distance that the body travels during a full stroke cycle, and stroke rate is defined as being the number of full strokes performed within a given period of time. The relationship between stroke length, stroke rate and swimming velocity for different events (race distance and stroke technique) has been one of the major points of interest in biomechanical research of competitive swimming since the pioneering study of East (1970). Throughout an event, the decrease in swimming velocity is related to a decrease in stroke length in all swimming strokes (Craig et al., 1985; Hay and Guimarães, 1983). Moreover, swimmers try to increase velocity, maintaining stroke length as high and constant as possible and increasing the stroke rate (Craig et al., 1985). Stroke length seems to represent an important parameter to verify differences between elite and non-elite swimmers. Indeed, for a given event, high-level swimmers have higher values for stroke length than lower-level swimmers (Leblanc et al., 2007; Seifert et al., 2008). Comparing several race distances, in longer events, all stroke parameters have a tendency to decrease (Craig and Pendergast, 1979; Seifert et al., 2008). Comparing swimming strokes by distance, there is a trend for stroke rate and velocity to decrease and a slight maintenance of stroke length with increasing distances (Jesus et al., 2011; Chollet et al., 1996).

One other variable often used to assess stroke cycle kinematics is the stroke index, considered as an estimator for overall swimming efficiency (Costill et al., 1985). This parameter assumes that, at a given velocity, the swimmer with greater stroke length has the most efficient swimming technique. Regarding swimming techniques, the front crawl is the one with the highest stroke index, followed by backstroke, butterfly and breaststroke (Sánchez and Arellano, 2002). Regarding swimming distance, Sánchez and Arellano (2002) reported a trend for stroke index decrease from the 50 m to the 200 m events, except in the breaststroke. Nevertheless, Jesus et al. (2011) did not find the same decrease in stroke index from shorter to longer distances in World Championship finalists. There was only a significant effect of distance on stroke index for the female swimmers. Regarding swimming level, higher-level swimmers have higher efficiency, which is reflected by a higher stroke index (Jesus et al., 2011; Sánchez and Arellano, 2002).

When comparing World Championship medalists and remaining finalists, there were no significant differences in stroke kinematics between medalists and non-medallists (Jesus et al., 2011). Jesus et al. (2011) suggested that differences between them might be explained by other variables, such as limb kinematics and anthropometrics. However, some papers report that the prediction of children’s swimming performance can be based on kinematic variables. Saavedra et al. (2003) and Vitor and Böhme (2010) reported that the stroke index for boys and the mean velocity of a 50 m maximal bout for girls were included in final prediction models. Moreover, in both genders, from 9 to 22 years old, increases in the swim velocity for the 50 m freestyle event occur due to increases in stroke length and stroke index (Morales et al., 2010).
Stroke length, stroke rate and stroke index depend on limb kinematics. For all swimming techniques, the last phases of the underwater stroke cycle have been presented as having a determinant role for propulsion (Schleihauf, 1979). Higher swimming velocities are achieved by increasing the partial duration and the propulsive force during the final actions of underwater curvilinear trajectories (Barbosa et al., 2011), especially during the insweep and upsweep phases of the front crawl and butterfly, the insweep phase of the breaststroke and the downsweep phase of the backstroke. Even if most of the propulsion (85 to 90 percent) is generated by upper-limb actions in front crawl (Deschodt, 1999; Hollander et al., 1988), lower-limb propulsion should not be disregarded. Therefore, Arellano et al. (2006) suggested that the reduction of the kick amplitude and the increase in kick frequency combined with the increase of knee angle during the downbeat to increase the swimmer’s velocity. This remark can also be applied in the other swimming techniques, with the exception of breaststroke, since lower-limb actions in this technique are very different. During the breaststroke, analysis has been done on the total time gap between upper- and lower-limb propulsive actions (Seifert and Chollet, 2008) and on the differences between undulation and flat variation of this technique (Persyn et al., 1991). However, Lyttle and Keys (2006) modeled swimmers performing two kinds of underwater dolphin kick and demonstrated an advantage of using a high-amplitude and low-frequency dolphin kick over a small, fast kick based on the velocity range with which underwater dolphin kicks are used. In addition, changes were also made to the input kinematics (ankle plantar flexion angle) to demonstrate that when gliding at 2.18 m.s⁻¹, a 10° increase in ankle plantar flexion could create greater propulsive force during the kick cycle. These results demonstrated that increasing angle flexibility could increase stroke efficiency during lower-limb actions.

Swimming velocity and the swimming energy cost are also dependent on the intra-cyclic variation in horizontal velocity. Higher velocities lead to lower intra-cyclic variation in horizontal velocity. In addition, increasing intra-cyclic variation in horizontal velocity leads to an increase in the energy cost of swimming, even when controlling for the effect of the velocity (Barbosa et al., 2006). Lower intra-cyclic variation in horizontal velocity leads to higher swim efficiency in all swimming techniques. However, in breaststroke and butterfly, higher intra-cyclic variation can be observed. For instance, during the breaststroke, more pronounced body waving imposes a decrease in intra-cyclic variation in horizontal velocity (Sanders et al., 1998; Silva et al., 2002). During the butterfly stroke, a low velocity during hand entry, a high hand velocity during the upsweep and a high velocity of the second downbeat will decrease the intra-cyclic variation and thus lower the energy cost and enhance swimming performance (Barbosa et al., 2008).

**Kinetics**

Kinetic analysis in swimming has addressed the understanding of two main topics of interest: (i) the propulsive force generated by the propelling segments; and (ii) the drag forces resisting forward motion, since the interaction between both forces will influence the swimmer’s velocity.

Regarding propulsive force, most research has been developed on upper-limb propulsion and less attention has been given to the lower limbs. This is probably because of difficulties involving direct measurement of propulsive forces acting on a free swimming subject (Marinho et al., 2009b) and because of the minor relative importance of the lower limbs to overall swimming propulsion (Deschodt, 1999). Thus, one of the most discussed issues in swimming hydrodynamics research is the relative contribution of drag and lift forces to overall upper-limb propulsion. Sato and Hino (2002) used a numerical approach, finding values for drag coefficient to be higher than those for lift coefficient at all angles of attack. From the results of these
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Simulations, the authors concluded that the resultant force was maximal with an angle of attack of the hand of 105° and the direction of the resultant force in that situation was −13°. Based on this analysis, Sato and Hino (2002) suggested that swimmers should stroke backward and with a little-finger-ward, outsweep motion, to produce the maximum thrust during the stroke. Schleihauf (1979) also reported that lift coefficient values increased up to an attack angle around 40° and then decreased. Drag coefficient values increased when the attack angle was increased and they were less sensitive to sweepback angle changes. In a more detail analysis, Bixler and Riewald (2002) found that hand drag had a minimum value near angles of attack of 0° and 180° and a maximum value was obtained near 90°, when the hand was nearly perpendicular to the flow. Hand lift was almost negligible at 95° and peaked near 60° and 150°. Recently, Marinho et al. (2011a) confirmed the supremacy of the drag component of the propulsive force, although an important contribution of lift force to the overall propulsive force production by the hand/forearm, in swimming phases when the angle of attack was close to 45°.

Understanding the basis of the propulsive force production can play an important role in swimmers’ technical training and performance. The fingers’ relative position during the underwater path of the stroke cycle is one of these cases. A large inter-subject range for fingers’ relative position can be observed during training and competition, with respect to finger-spreading and thumb position (Marinho et al., 2010a, 2009c). Marinho et al. (2010a) found that for angles of attack higher than 30°, the model with little distance between fingers presented higher values for drag coefficient compared to the models with fingers closed and with a large finger spread. For attack angles of 0°, 15° and 30°, the values of drag coefficient were very similar in the three models of the swimmer’s hand. In addition, the lift coefficient seemed to be independent of finger spread, showing few differences between the three models. However, Marinho et al. (2010a) were able to note slightly lower values for lift coefficient for the position with larger distance between fingers. These results suggested that swimmers create more propulsive force with the fingers slightly spread. Moreover, Marinho et al. (2010b) showed that the position with the thumb abducted yielded slightly higher values for drag coefficient compared to thumb-abducted positions. Furthermore, the position with the thumb fully abducted allowed an increase of the lift coefficient of the hand at angles of attack of 0° and 45°. Although there are some differences in the results of different studies (Schleihauf, 1979; Takagi et al., 2001; Marinho et al., 2010b), the main results seem to indicate that, when the thumb leads the motion (sweep back angle of 0°), especially during insweep phases, a hand position with the thumb abducted would be preferable to an adducted thumb position.

Regarding drag, this force can be defined as an external force that acts on the swimmer’s body parallel to, but in the opposite direction to, their movement direction. It depends on the swimmer’s anthropometric characteristics, equipment characteristics, physical characteristics of the water and the swimming technique (Marinho et al., 2011b). Kjendlie and Stallman (2008) found that active drag in adults was significantly higher than in children. This difference between adults and children was mostly due to different size and velocity during swimming. In addition, Marinho et al. (2010b) also studied active drag comparing boys and girls, reporting that there were no differences between them. This was due to the similar values of body mass and height in boys and girls found in this particular study.

Total drag consists of the frictional, pressure and wave drag components. Frictional drag is dependent on water viscosity and generates shear stress in the boundary layer. The intensity of this component is mainly due to the wet surface area of the body, the characteristics of this surface and the flow conditions inside the boundary layer. Pressure or form drag is the result of a pressure differential between the front and the rear of the swimmer, depending on velocity, the density of water and the swimmer’s cross-sectional area. Near the water surface, due to the
interface between two fluids of different densities, the swimmer is constrained by the formation of surface waves, leading to wave drag (Toussaint and Truijens, 2005).

The contribution of friction, pressure and wave drag components to total drag during swimming is an interesting research issue in sports biomechanics. It is mostly accepted that frictional drag is the smallest component of total drag, especially at higher swimming velocities, although this drag component should not be disregarded in elite-level swimmers. Bixler et al. (2007), using a numerical approach, found that friction drag represented about 25 percent of total drag when the swimmer is gliding underwater. Zaidi et al. (2008) also reported an important contribution of friction drag (~20 percent) to the total drag when the swimmer is passively gliding underwater. Hence, matters related to sports equipment, shaving and the decrease of immersed body surface should be considered in detail, since this drag component seems to influence performance, especially during the underwater gliding after starts and turns (Barbosa et al., 2011). On the other hand, pressure and wave drag represent the major part of total hydrodynamic drag, thus swimmers must emphasize the most hydrodynamic postures during swimming (Maglischo, 2003; Marinho et al., 2009d). Although wave drag represents a large part of total drag during swimming (Kjendlie and Stallman, 2008), this drag component diminishes significantly when gliding underwater. Lyttle et al. (1999) concluded that there is no significant wave drag when a standard adult swimmer is at least 0.6 m under the water’s surface. Moreover, Vennell et al. (2006) found that a swimmer must be deeper than 1.8 and 2.8 chest depths below the surface for velocities of 0.9 m.s⁻¹ and 2.0 m.s⁻¹, respectively, to avoid significant wave effects.

Neuromuscular response during swimming

Compared to kinematic and kinetic research studies, neuromuscular assessments have not been used as much in competitive swimming research (Barbosa et al., 2010c). The main aim of this approach is to understand the dynamics of neuromuscular activity between strokes during limb and trunk actions. Ikai et al. (1964), in their pioneering study of neuromuscular activity in swimming, showed that the bicep braquialis, the triceps braquialis, the deltoid and grand dorsal were highly activated during strokes, with the elbow extensors presenting a higher activation than the elbow flexors during front crawl, butterfly and breaststroke. Following this study, Lewillie (1973) compared different strokes at different velocities and observed the highest neuromuscular activation for the butterfly when swimming at maximum velocity. Moreover, increasing velocity led to an increase in anterior rectum and triceps surae activation in all strokes. Nuber et al. (1986) observed high activation of the latissimus dorsi and pectoralis major during underwater phases of the stroke cycle, whereas supraspinatus, infraspinatus, middle deltoid and serratus anterior showed high activation during the recovery phases of the front crawl, breaststroke and butterfly. Additionally, Pink et al. (1991) reported similar activation for the pectoralis major and latissimus dorsi to propel the body and for the infraspinatus to externally rotate the arm at the middle of the arm’s recovery during the front crawl. Pink et al. (1991) also observed high activation for the three heads of the deltoid and the supraspinatus during the arm’s entry and exit. These authors presented an important concern regarding injury problems, especially related to high levels of activation of the serratus anterior and the subscapularis. Therefore, coaches and swimmers should be aware of this to help prevent injuries. Barthels and Adrian (1971) suggested that the trunk movement during the butterfly stroke is associated with lower-limb actions, reflected by the greater activity of the rectus abdominus and the spine erector. In breaststroke, Ruwe et al. (1994) demonstrated consistent activation for the serratus anterior and teres minor muscles throughout the stroke cycle.
More recently, neuromuscular response has been used to study muscle fatigue and its relationship to limb kinematics, using spectral analysis procedures, which can give important data to coaches and swimmers (Dimitrov et al., 2006; Figueiredo et al., 2010). For instance, Aujouannet et al. (2006) reported that, in a fatigued state, the spatial hand path remained unchanged, with a greater duration of the catch, the insweep and the outsweep phases during the front crawl. Moreover, fatigue analysis showed an increase in latissimos dorsi and triceps braquialis during all-out 100 m front crawl swimming (Stirn et al., 2010). When increasing distance to 200 m, the inability to maintain swimming velocity in the last laps was related to the increase of fatigue indices for the flexor carpi radialis, biceps brachii, triceps brachii, pectoralis major, upper trapezius, rectus femoris and biceps femoris (Figueiredo et al., 2010).

**Running**

**Ageing and gender as factors of running performance**

In adults, the time to complete a race gradually increases with age. Marathon running among men and women is generally fastest, as indicated by world records, when individuals are 25–35 years old (Trappe, 2007). Nevertheless, a gradual performance decline should be expected in further years (Leyk et al., 2007; Trappe, 2007). This pattern can be associated with age-related declines in maximal and submaximal cardiorespiratory variables (Quinn et al., 2011). A decline in cardiovascular capacity of 0.5 percent per decade occurs in highly trained distance runners, while a 1.0 percent and 1.5 percent decline per decade occurs in moderately trained and untrained individuals, respectively (Trappe, 2007). Decline in sprint performances are expected with age as well. Sprint performance decline is only in the range of 2.6–4.4 percent per decade in 50–69 year-olds (Leyk et al., 2007). However, this decline becomes more apparent around 65–70 years (Korhonen et al., 2003). The deterioration of overall performance with age is primarily related to reduction in running velocity (5 to 7 percent per decade), stride length and an increase in contact time (Korhonen et al., 2003). Reductions in muscular strength and power may be the cause of this performance decline throughout sprint runners’ careers (Quinn et al., 2011). Despite the trend of performance declining with age in both endurance and sprint events, continued running late into life attenuates a decline in physiological function with age and is beneficial for overall health (Trappe, 2007).

Gender-specific differences are also apparent. Female times are about 10 percent (marathon) and 13 percent (half-marathon) above the corresponding times of their age-matched peers (Leyk et al., 2007). Traditionally, \( VO_{2\text{max}} \) has been the most important factor related to endurance running (Morgan and Daniels, 1994; Sjödin and Svedenhag, 1985). Earlier observations reported \( VO_{2\text{max}} \) values of 70–85 (ml.kg\(^{-1}\).min\(^{-1}\)) and 60–75 (ml.kg\(^{-1}\).min\(^{-1}\)) for international male and female runners, respectively (Davies and Thompson, 1979; Smith et al., 2000). Due to this data, distance performance differences are expected to remain fairly constant in the future (Sparling et al., 1998). In contrast to endurance running, the gap between men and women in sprint running has increased since 1952 (Seiler et al., 2007). Performance differences increased from 10.3 percent in the period 1976–1988 to 11.5 percent for the period 2000–2005 (Seiler et al., 2007). This observed change cannot be explained by declining women’s participation in sport, poorer training practice or reduced access to technological developments, but it does coincide with dramatic improvements in the scope and sensitivity of drug testing (Seiler et al., 2007). Added to that, underlying differences in muscle mass may also reflect the true sprint performance differences between males and females (Perez-Gomez et al., 2008).
Tactical factors and running performance

Due to their elite nature, top athletes are known to participate in a substantial number of competitions within the year. In most cases, they compete at the same distance several times within and between major competitions. So, small enhancements in performance from race to race are of trivial importance to be well placed or even win a medal in the most important events. Hopkins and Hewson (2001) determined a smallest worthwhile change of ~1 percent for half and full marathons and ~0.5 percent for shorter endurance events in faster adult male distance runners within one competitive season. Authors also stated that female runners, older runners and faster runners are less variable in their performance than male runners, younger runners and slower runners, when comparing within these three groups. Nevertheless, there are some tactical aspects of racing that runners can improve on from one event to another in order to achieve greater enhancements in performance.

The definition of the optimal pacing strategy during the race is one of the most important topics for long-distance runners. Since pacing strategy is regulated by a complex system that balances the demand for optimal performance, it is important to preserve homeostasis during exercise. Pacing strategies should only be used in exercises lasting longer than 80–100 s (van Ingen Schenau et al., 1994). Based on earlier observations, it seems that the optimal pacing strategy differs between events. Greater running speeds in the 800 m event are achieved in the first lap, and the ability to increase running speed on the second lap is limited (Tucker et al., 2006). On the other hand, in the 5,000 m and 10,000 m events, the first and final kilometers are significantly faster than the middle-kilometer sections (Tucker et al., 2006). The pace during the initial stage of a 5,000 m race can be 3 to 6 percent greater than the average race pace, without negatively impacting performance (Gosztyla et al., 2006). Added to this, conserving energy in the middle part of the race allows higher velocities to be reached in the final stages. This trend to demonstrate an ‘end spurt’ in the final stage of the race is common in world record breakers. Noakes et al. (2009) observed that, in their quickest mile races, world record athletes run the final lap faster than the second and third laps to overcome their opponents. World-class runners adopt a more aggressive pacing strategy requiring greater efforts than the less experienced runners, probably due to a greater mental commitment and/or a better capacity to run under fatigue (Hanon and Gajer, 2009). So, the acquisition of self-selected pace according to a runner’s ability is a major strategy for long-distance running. Faster marathoners tend to run at a more consistent pace compared with slower runners (March et al., 2011). They also have greater aptitude for ‘recalling pace’ throughout the race. ‘Recalling pace’ helps runners accurately approach their self-set target pace in a race (Takai, 1998). Competitive runners who used cognitive strategies to monitor their running pace and fatigue reproduced more accurate self-set target times during a 20 km intercollegiate race (Takai, 1998). Age and sex can also be considered determinant factors for pacing in a long-distance race. A recent investigation by March et al. (2011) determined that older athletes and female marathon runners are better pacers than younger and male marathon runners, respectively. Based on this evidence, it seems that the pacing strategy is not purely the result of developing fatigue throughout the race. Instead, it is an aspect that runners should regulate in anticipation, based on individual ability, in order to optimize performance.

Endurance races have a large number of participants. Competitors in such events tend to form groups throughout the race. While most of those groups are characterized by having runners from similar competitive levels, the positioning in a group is a factor determining performance. Approximately 95 percent of elite runners participating in the Fukuoka and Tokyo Marathons maintained a minimum distance of 0.5–1.5 m from other competitors and avoided occupying an angle of ±15 degrees either ahead or behind other runners (Yamaji and Shephard, 1987). It is
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possible that runners with strategic positioning will benefit from a drafting effect and save more energy during the race. This is even more common if athletes are attempting to win a medal in more than one event during a major championship. In this case, athletes need to run each event several times during the competition, which requires a sufficient recovery between races. Strategically, runners need to find other ways of preserving energy from one event to another. Brown (2005) observed that the female middle-distance runners who competed in both the 800 m and 1,500 m at the 2004 Olympic Games ran at the back of the leading group during the early stages, with the purpose of saving energy for further races. This tactical approach of track positioning will also determine the total distance covered in the race. Despite the race distance being initially determined, runners can run wide on bends to overcome their opponents. This suggests that different runners can cover different distances within the same race. Indeed, the fact of going wide to overtake other runners will require an increase in running velocity and will require a higher amount of energy. Jones and Whipp (2002) observed that the winners of the 800 m and 5,000 m finals during the 2000 Olympic Games were the runners who were able to ration their metabolic resources to better effect by running closer to the actual race distance. So, runners should be conscious of minimizing the distance covered in races and have a good positioning in the group if they wish to optimize their performance.

The tactical factors affecting endurance performance differ from those affecting sprint races. For sprinters, the reaction time to the starter’s gun should be especially important, as this is a greater factor in determining the outcome of the race than it would be in longer distance races. Collet (1999) observed that most world-class sprinters try to anticipate the start signal. The procedures presently used to start the Olympic sprint events may also influence reaction time.

Sprint performance also relies strongly on a fast acceleration at the start and on the capacity to maintain a high velocity in the remainder of the race. In this case, the best pacing strategy is an all-out effort, even if this strategy causes a strong reduction in velocity at the end (van Ingen Schenau et al., 1994). The acquisition of maximal speed is mainly limited by the ability to accelerate the legs in forward and backward directions, determining the stride frequency and stride length during the race. Salo et al. (2011) reported a large variation in performance patterns among the elite sprinters in terms of stride frequency or stride length reliance. Running velocity seems to be highly dependent on the running technique according to the runners’ individual characteristics. In this sense, coaches should take this reliance into account in their training.

Environmental factors and running performance

External factors such as environmental conditions can also influence race finish time. In running events, air temperature, humidity, air pollution (particularly in the marathon) and wind direction should be considered in detail. There is evidence that air temperature has a strong correlation ($r = 0.66–0.73$) with finishing time of races (Vihma, 2010). Marathon performance times are progressively slow in races where temperatures rise above 5–10°C (Ely et al., 2007; Montain et al., 2007). Indeed, elite male and female performances seem to be affected by race temperature similarly (Montain et al., 2007). The results of three Japanese Championship Marathons showed that the difference between the first and one-hundredth-placed finishers was the same in cool (5–10°C) as in warm (15.1–21°C) conditions (Ely et al., 2008). By contrast, increases in air temperature induce a greater penalty in the performance of slower runners (Ely et al., 2007; Vihma, 2010). This negative effect of warmer weather on the finishing times of slower runners remains even throughout races, while in faster runners, the effect of higher race temperatures is a deceleration in the latter stages (Ely et al., 2008). In some cases, withdrawal from the race is an
option more likely to be taken by non-elite runners in hot conditions. Vihma (2010) reported that the percentage of non-finishers in the annual Stockholm Marathon from 1980 to 2008 was significantly affected ($r = 0.72$) by the air temperature and specific humidity. Air pollution is also an important external aspect to be considered during long-distance races since performance depends on an optimal lung function. The air pollution present during marathons rarely exceeds health-based national standards and levels known to affect lung function in laboratory situations (Marr and Ely, 2010). However, air pollution levels above the minimum known to affect lung function during exercise may decline performance by 1.4 percent in the marathon, especially for women (Marr and Ely, 2010).

The effect of wind on sprint times is also of considerable interest to runners and coaches. This environmental factor is a particular problem in outdoor sprint running events, which start and finish at different points on a 400m track. In some circumstances, wind conditions can delay runners reaching their maximum velocity. The disadvantage of headwind seems to be greater than the benefit of tailwind of the same magnitude (Linthorne, 1994). Several authors used mathematical models to gain new insights into the effect of wind assistance on sprinting performance. The most favorable wind conditions are shown to be a wind speed of no more than 2 m.s$^{-1}$, assisting the athlete in the back straight and around the second bend (Quinn, 2010). In the case of headwind, runners should adopt new tactical approaches or modify certain performance patterns to minimize these conditions. Changes in body lean angle in windy situations have little effect on improving performance (Ward-Smith, 1999a). In addition, the outside lane (lane 8) is shown to be considerably faster than the favored center lanes (Quinn, 2010). The use of improved clothing or covering the hair may also lower wind resistance and, as a consequence, aerodynamic drag (Kyle and Caiozzo, 1986).

In summary, studies in real competition conditions are a more accurate way of analyzing performance behavior than laboratory or field tests. Based on scientific evidence from such studies, coaches and runners can manipulate their training and race strategies accordingly.

**Cycling**

**Energetics of cycling**

Cycling performance would appear to be largely dictated by the ability of the cyclist to produce high power outputs at minimal metabolic cost. Physiological factors are known to influence mechanical power production and consequently the cycling performance.

**Anaerobic**

Anaerobic power in cycling is relevant for sprint cycling. A very high power output during 30s of cycle sprinting uses essential sources of phosphocreatine degradation and glycogenolysis, ending in lactate production. Phosphocreatine degradation reaches a maximal rate within 10s and ceases to contribute to energy production (Gaitanos et al., 1993).

High lactate production may be due to contributions of anaerobic glycogen and glucose metabolism (Ward-Smith, 1999b) or due to aerobic overproduction of pyruvate and subsequent conversion to lactate (Conley et al., 2001). The higher the exercise intensity, the higher the rate of energy uptake and release of lactate. For example, it is interesting to note that at three and five minutes after completion of the one-hour world record, lactate levels were 5.2 and 5.1 mmol.L$^{-1}$ (Padilla et al., 2000). Nevertheless, it is well documented that lactate reaction is important for maintaining the cytosolic redox and letting glycolysis continue during
intensive exercise. Thus, for a given VO₂ during cycling, high lactate production is beneficial and its production is even more beneficial if accompanied by a high capacity for lactate and proton transport from the cell. These factors are known to increase with endurance and sprint training (Juel, 1998).

Analyzing the biomechanics of cycling, a higher pedal rate requires greater VO₂ for a given output because of an increase in internal work for repetitive limb movements (Brisswalter et al., 2000). The contraction time is reduced and blood flow to the type I fiber muscles is enhanced. At the same time, muscle fatigue is reduced in muscle type II fibers. However, when pedal cadence is increased without reduction in force to the pedal, type II muscle fibers become progressively recruited. Increasing type II muscle fiber recruitment will contribute to acidosis because they have less mitochondrial mass to facilitate ATP regeneration and the uptake of protons (Robergs et al., 2004).

**Aerobic**

Cyclists in long-distance events are well known to have high aerobic power and capacity, in order to accomplish their competition events. There is substantial scientific evidence demonstrating that successful cyclists possess high values of VO₂max and their lactate threshold (that corresponds to the exercise intensity, eliciting a lactate concentration of 4 mmol.L⁻¹) is equivalent to a high percentage of VO₂max of the cyclist (Fernandez-Garcia et al., 2000). For male cyclists, the mean VO₂max during Le Tour de France and La Vuelta a España was found to be 73.5 mL.kg⁻¹.min⁻¹ and the lactate threshold was observed to be 90 percent of VO₂max (Fernandez-Garcia et al., 2000). This last parameter has been reported as the highest possible steady state of work intensity that can be maintained for a long period of time. As one could note, the best cyclists could perform high-intensity exercise without increasing blood lactate concentration. Padilla et al. (2000) studied road-racing cyclists and found that they have obtained high values of VO₂max (78.8±3.7 mL.kg⁻¹.min⁻¹), high values of maximal heart rate (192±6.0 beat.min⁻¹) and high values of peak power (431.8±42.8 W).

Pfeiffer et al. (1993) have demonstrated that VO₂max is a strong predictor (r = −0.91) of cycling performance in a 14-day stage race among trained female cyclists. Accordingly, it appears that a reduced VO₂max may be indicative of fatigue or overtraining, helping coaches to adjust and to re-plan the training process. However, it seems that lactate parameters provide a better predictor of endurance performance than oxygen consumption. VO₂max is limited by the oxygen supply to the muscle mitochondria (Saltin and Strange, 1992; Wagner, 1995). On the other hand, lactate levels are related to the capacity to transport lactate and hydrogen ions or proton (H⁺) out of the muscle fibers, and the capacity of skeletal muscle to utilize lactate. Central factors are expected to limit VO₂max, while the lactate response to exercise is primarily related to peripheral factors in trained athletes. Muscle performance is dependent on the percentage of slow-twitch fibers, the activities of key oxidative enzymes and respiratory capacity (Sjodin and Jacobs, 1981).

Additionally, the power related to the weight of the cyclist is considered determinant to competitive cyclists. A power/weight ratio of more than 5.5 W.kg⁻¹ is considered a necessary prerequisite for top-level performance (Palmer et al., 1994). Lucía et al. (2001a, 2001b) assessed this variable during the most important cycling road races, and data suggest that high power output to body mass ratio (≥6 W.kg⁻¹) at maximal or close to maximal intensity is a prerequisite in professional cyclists.

Regarding the efficiency of cycling, recent studies indicated that mechanical efficiency seemed to increase with rising exercise intensity in professional cyclists (Lucía et al., 2002). It
seems that these cyclists acquire a high cycling efficiency, allowing them to sustain high workloads for extended periods of time. This is only possible because they reveal substantial resistance to fatigue of recruited motor units at high submaximal intensities (Lucía et al., 2001a, 2001b). Total volume and workloads, alongside the years dedicated to cycling, could have some impact in this efficiency. Professional riders generally cycle 35,000 km per year and compete for 90 days (Lucía et al., 2002). These facts certainly help to develop different physiological and mechanical adaptations, which improve efficiency. During heavy exercise, the efficiency appears to be positively related to the percentage of type I fibers in the vastus lateralis muscle (Horowitz et al., 1994). A higher proportion of type I fibers in the muscle is associated with a lower submaximal oxygen cost, and thus a greater gross efficiency (Coyle et al., 1992). This efficiency is a reflection of the increase in aerobic metabolism and related increases in muscle power output.

When cycling, breathing pattern can also influence energy expenditure. The oxygen cost of breathing can be very meaningful in highly fit individuals and has been estimated to be about 15 percent of \( \dot{V}O_2_{\text{max}} \) (Harms, 2000). The work of breathing during heavy exercise compromises leg blood flow to working limb muscle. Consequently, a more efficient breathing pattern may avoid reduction in blood flow to the working muscles.

Heart-rate response seems to be related to course profile. In individual time trial stages of a tour, cyclists have been found to reach a mean value of approximately 171 beat.min\(^{-1}\), while in flat stages they reached an average of 125 beat.min\(^{-1}\). During a mountain stage, mean heart rate values are approximately 132 beat.min\(^{-1}\) (Fernandez-Garcia et al., 2000).

Another important concern is related to dehydration and hyperthermia during endurance cycling performance. Coyle (1999) stated that dehydration during exercise promotes hyperthermia by reducing skin blood flow, sweating rate and thus heat dissipation. The combination of dehydration and hyperthermia during exercise causes large reductions in cardiac output and blood flow to the exercising musculature, and thus has a large potential to prejudice endurance performance (Coyle et al., 1992). Therefore, coaches and cyclists should be aware of nutrition during training and competition to prevent hypoglycemia and attenuate dehydration and hyperthermia, especially in long cycling events.

**Biomechanics of cycling**

One of the greatest points of interest to researchers is the biomechanics of cycling. Pedaling technique, aerodynamics of the system, bicycle equipment and cyclist and anthropometric characteristics are some of the most important determinants of cycling performance.

**Pedaling technique**

Pedal rate can influence both the ability to produce power as well as the rate of energy consumption. Abbiss et al. (2009) suggested that cadence selection could have a significant influence on cycling performance. Although there is no agreed criterion to support the optimal cadence, the existing literature suggests that it can influence neuromuscular fatigue in active muscle groups (Takaishi et al., 1994). There is a trend for racing cyclists to ride at more than 90 RPM, whereas novice cyclists tend to use lower pedal rates (Garnevale and Gaesser, 1991). Additionally, when the cyclist is using the various gear ratios, cadence varies between 70 and 100 RPM. Optimal and self-selected cadences have been found to be influenced by cycle intensity (Marsh and Martin, 1997), course geography (road slope) (Lucía et al., 2001a) and cycling experience (Marsh and Martin, 1997). Maximal aerobic output allows the cyclist to use higher cadence (Nesi et al., 2005). At the same time, higher cadence causes a higher mechanical power output.
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When compared to road cycling, uphill cycling typically corresponds to a higher cadence (Millet et al., 2002) and this higher cadence is also used during drafting (Hausswirth et al., 1999). A single pedal rate is not expected to be beneficial for all cyclists. In its place, the optimal cadence during cycling depends on central (i.e. VO\textsubscript{max}) and peripheral physiological characteristics (i.e. muscle fiber contraction). Much more research is still required in this area since there is considerable discrepancy in the existing literature.

Cadence is shown to affect force effectiveness (Candotti et al., 2007; Loras et al., 2009) and gross efficiency (i.e. Foss and Hallen, 2004, 2005). These are two parameters usually used to indicate the quality of pedaling technique (i.e. Candotti et al., 2007; Korff et al., 2007; Zameziati et al., 2006). Force effectiveness is the ratio between the forces directed 90° on the crank arm and the total force on the pedal. In a mechanically effective pedaling technique, a large component of the generated force is directed perpendicularly on the crank arm. Forces directed otherwise do not contribute to mechanical work rate and the associated energy cost is wasted. However, mechanical constraints within the rider–bicycle system can cause the generation of considerable radial forces (Kautz and Hull, 1993).

Gross efficiency is viewed as an indicator of the total metabolic rate, and it is believed that high gross efficiency is related to good technique in general (Candotti et al., 2007; Zameziati et al., 2006). Some studies have demonstrated a moderate-to-strong relationship between force effectiveness and gross efficiency (Candotti et al., 2007; Zameziati et al., 2006). Leirdal and Ettema (2011) verified that cadence has a negative and similar effect on both force effectiveness and gross efficiency. When the cyclists used higher cadence, force effectiveness was lower and consequently gross efficiency decreased. Higher pedaling rates increase the non-muscular component of the pedal forces and this increasing inertial force affects force effectiveness in a negative way (Kautz and Hull, 1993). Leirdal and Ettema (2011) found no effects regarding body orientation or seat position on gross efficiency, force effectiveness or on the relationship between them.

Aerodynamics

Aerodynamic drag force is composed of two forms of drag: pressure and skin-friction drag (Millet and Candau, 2002). Air resistance while cycling is the primary energy cost factor at high speeds. It is the most determinant performance variable at 50 km.hour\textsuperscript{-1} (Gross et al., 1983; Kyle, 1991) and it represents more than 90 percent of the total resistance of cycling at 30 km.hour\textsuperscript{-1} (Kyle, 1991). Therefore, the configuration of the bicycle and its components, as well as body position of the cyclist, are of great importance, and ways to reduce this drag force have been deeply studied. For a constant power output, decreasing aerodynamic drag would result in an increase in velocity of the cyclist–bicycle system. Considering that the mechanical power output can be assumed to be the sum of the energy used to overcome the total resistive forces (De Groot et al., 1995; di Prampero, 2000), the optimization of aerodynamic drag could be fundamental in enhancing the cyclist’s performance. Some of the most important parameters influencing aerodynamic drag are: (i) the combined projected frontal area of cyclist and bicycle; (ii) the drag coefficient; (iii) air density; and (iv) the velocity relative to the air (di Prampero et al., 1979).

The effective frontal area is the dominant component of aerodynamic drag and its estimation allows assessment of the cyclist’s profile and the optimal riding position for the drag decrease to be determined (Debraux et al., 2011). Frontal surface area represents the portion of the body which can be seen by an observer placed exactly in front of the body. This pressure drag resultant represents the differential air pressures that exist between the front and rear of a moving body. This is mainly dependent on the general size and shape of the body. Skin-friction drag is
the resistance generated by the friction of fluid molecules directly on the surface of the body in motion (Millet and Candau, 2002). Grappe (2009) showed that the relationship between effective frontal area and the air velocity was hyperbolic. Regarding skin drag, a special wax cover allows an increase in the velocity of the cyclist–bicycle system at the same mechanical output for the range of cycling velocities between 8.7 m.s⁻¹ and 11 m.s⁻¹ (Grappe, 2009). The importance of the cyclist cover was confirmed by Oggiano et al. (2009), who observed the aerodynamic drag to be dependent on the velocity and the roughness of the textile. However, for greater velocities, these differences were not observed. These findings demonstrated the complexity of the relationship between drag coefficient, air velocity and surface roughness.

It was verified that the drag coefficient decreases when body mass increases (Heil, 2001). It was supposed that a higher body mass corresponds to higher body surface area and consequently should correspond to a higher drag coefficient. However, in road racing, when related to body weight, the frontal drag of the smaller cyclists was greater than larger cyclists (Swain, 1994). Moreover, the ratio of body surface to frontal area is larger in smaller cyclists and creates a greater relative air resistance (Cappelli et al., 1993; Swain, 1994). The variation in the drag coefficient is more complex than evaluating the projected frontal area. Its relation with velocity remains difficult to understand and more research is needed to study its characteristics (Debraux et al., 2011).

Added to the air resistance, one cannot neglect the resistance caused by the rolling wheels. Rolling resistance is caused by the compression of the wheel and/or the ground (di Prampero et al., 1979). At low velocity, this affects power output more than air drag (Faria and Cavanagh, 1978). A small-wheeled bicycle demonstrated more resistance to motion than a large-wheeled one, and thus resistance seemed to be inversely proportional to the radius of the wheel (Faria and Cavanagh, 1978). Tire pressure and the specific characteristics of the tire can also have an effect on rolling resistance. Higher pressure and sew-up tires increase cycling efficiency (Faria and Cavanagh, 1978).

It is important to recognize that the drafting effect is a component that tends to reduce the air forces opposing the cyclists and the energy utilization by approximately 40 percent (Lucía et al., 2001b). Hausswirth et al. (1999) verified that at a velocity of 39.3 km.hour⁻¹ drafting resulted in a 14 percent reduction for oxygen consumption, a 7.5 percent reduction for heart rate and a 30 percent reduction for expiratory volume. However, these parameters do not change when the cyclists constantly alternate the lead. Drafting reduces the air resistance in the middle of the pack by as much as 40 percent (McCole et al., 1990), and consequently reduces the energy cost. These details could be important to the race, considering that cyclists can use this information to optimize their performance. The tactics used in interaction with the other cyclists, knowing the importance of energy saving, can lead the cyclist to achieve better results. When racing, the cyclist is integrated in a group of elements competing against each other. At the same time, this group is a dynamical and self-organizing system within which the system’s elements also have periods of cooperative interaction (McGarry et al., 2002). Waldron et al. (2011) introduced the effect of ‘swarming’ in cycling, demonstrating the presence of attract-and-repel elements during different points of the race. Simultaneously, they verified that breakaways caused longer attract-and-repel phases, perturbing the system complex. A perturbation is considered an event that causes a disruption in the reciprocal rhythm and stability of a system. This incident can result in a turn of events affecting the performance of cyclists.

**Equipment: bicycle and cycle vest**

The equipment configuration, bicycle and even the cyclist’s clothing influence the cyclist’s performance (Gonzales and Hull, 1989; Too, 1991). The seat tube angle is an important variable of
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equipment configuration that has an effect on performance. Increasing this angle (above 78.5° for the smaller cyclists and above 73.2° for the tallest cyclists) leads to changes in the hip angle and, consequently, changes in the length of the muscles crossing the hip joint. An increased seat height allows a forward and more crouched position, resulting in a decreased air resistance. Subsequently, cycling velocity will increase (Heil et al., 1995). The use of aerodynamic frame and wheels also affects the cyclist’s performances. Jeukendrup and Martin (2001) showed improvements of more than two seconds in a 40 km time trial. This improvement in time trials demonstrates the importance of the utilization of correct and appropriate equipment. Moreover, it is also necessary to consider the weight of the equipment and the cyclist’s vest in order to get better performances.

Anthropometrics
Time-trial cyclists are usually taller and heavier than uphill cyclists (Padilla et al., 1999). When climbing, the cyclist moves slowly and the force of gravity is the main resistance to overcome. Therefore, an increased body mass has a negative effect on the cyclist’s velocity (Swain, 1994). In shorter cycling events, taller cyclists seem to be more successful, while shorter cyclists are more successful at longer distances (Craig and Norton, 2001). The cyclist’s anthropometric characteristics are essential and can have an important impact on other biomechanical aspects, as seen before (e.g. aerodynamics), and also on bioenergetics. For instance, Coyle (2005), when analyzing Lance Armstrong, reported that, during the months leading up to each of his seven Tour de France victories, he reduced body mass and body fat by 4–7 kg. Therefore, over a seven-year period, an improvement in muscular efficiency and reduced body fat contributed to a remarkable 18 percent improvement in his steady-state power per kilogram of body mass when cycling at a given O2. (Editor’s note: the US Anti-doping agency stripped Armstrong of the seven Tour de France titles in August 2012.)

Triathlon
Anthropometrics, energetics and biomechanics
An excess of body fat in swimming decreases the body’s need to expend more energy to increase the buoyancy and thermal resistance to cold water, due to the subcutaneous layer of adipose tissue. However, during running, energy expenditure is related to body mass by the need to raise and lower the body’s center of mass and to accelerate and decelerate the legs, moving the total body weight. In cycling, the athlete has to move their body mass and the mass of the bicycle to produce movement (Bentley et al., 2002; Gnehm et al., 1997). It is possible that smaller triathletes may perform better, taking advantage of the drafting effects in swimming and cycling. However, there is not sufficient scientific evidence for this. The triathlon is a long-duration sport (about two hours) and it is associated with typical aerobic physiological characteristics. Maximal heart rate in triathletes has been observed to be 6 to 10 beat.min⁻¹ lower in cycling compared to runners (Roeecker et al., 2003). However, there is also evidence that heart rate may not differ between cyclists and runners (Bassett and Howley, 2000). Aerobic capacity has been identified as the main component to maintain high exercise intensity, especially during the running section of the triathlon (Dengel et al., 1989). Athlete performance in the Olympic triathlon is highly correlated with anaerobic threshold (De Vito et al., 1995; Holly et al., 1986). It is suggested that VO₂max sets the upper limit of the aerobic capacity and the performance depends on the ability of the triathlete to exercise at a higher fractional utilization of the VO₂max (Coyle,
1995). In contrast to other endurance sports, such as cycling and running, only a few studies reported \( \text{VO}_2 \) kinetics parameters in triathletes, and more research is needed on this matter. It is important to notice that a great part of the existing research in triathlon separates the sports when testing, and it is important to be cautious about the possible effects of swimming prior to cycling and of cycling prior to running.

Regarding movement kinetics, the existing literature on triathletes is very scarce. According to Toussaint (1990), the swimmers have a greater distance per stroke and a lower stroke frequency than the triathletes (1.23 m vs. 0.92 m), providing a higher swimming velocity (1.17 m.s\(^{-1}\) vs. 0.95 m.s\(^{-1}\)). Triathletes require more power to produce movement (\( \sim \)45 W) than swimmers (\( \sim \)32 W). Regarding running, kinematics and muscle recruitment were altered in 46 percent of moderately trained triathletes after a 45-minute cycle (Bonacci et al., 2010). There were registered changes in the angle of the ankle and these were associated with the changing running economy after cycling. On the other hand, in cycling, it has been shown that freely chosen cadence in triathletes is about 90 RPM in submaximal exercise (Lepers et al., 2001), which is close to the cadence used in elite cycling (Lucía et al., 2001b).

**Swimming, cycling and running**

A successful triathlete takes between one hour 45 minutes and two hours to complete the total Olympic distance. The swimming split is suggested to be 15 percent of their total competition time, with 55 percent spent on the bicycle and 29 percent running (Landers et al., 2008). The two initial sections, swimming and cycling, are important for getting into a good position for the running section. The running section is the section most correlated with the overall performance in the Olympic-distance triathlon (Fröhlich et al., 2008).

Swimming is performed in open water and the conditions (temperature, water salinity, turbulence) are highly variable. When the water is below 20ºC, triathletes are allowed to use a wetsuit of a maximum of 5 mm thickness. These wetsuits are believed to increase athletes’ performances by reducing drag (Chatard et al., 1995), increasing buoyancy and hydrostatic lift (Chatard and Millet, 1996). Regarding swimming technique, elite swimmers are more efficient than elite triathletes (Toussaint, 1990). Though having a similar stroke rate, the swimmers presented higher stroke length, resulting from greater propelling efficiency (Toussaint, 1990). Therefore, stroke length could be a good parameter to assess the technical improvement of a triathlete during the season. Another important variable which has gathered scientific attention is drafting. This occurrence is related to the effects of the displacement of the athlete when he is immediately behind another. The depression made in the water by a leading swimmer seems to decrease the passive drag of the following swimmers by 10 to 26 percent (Chollet et al., 2000; Millet et al., 2000a). Silva et al. (2008) used computational fluid dynamics to verify lower values of drag coefficient in the back swimmer until \( \sim \)8 m of distance between the swimmers. Thus, drafting could be beneficial to the energy cost of the swimmer when exposed to suction effect (Bassett et al., 1991; Cholard and Wilson, 2003; Hausswirth et al., 2001). Blood lactate concentration is reduced (from a mean value of 5.0±0.5 to 3.4±0.6 mmol.L\(^{-1}\)), as well as rating of perceived exertion (from a mean value of 14.9±0.5 to 11.7±0.4) in the back swimmer (Bassett et al., 1991). Improved swimming economy is also reflected in oxygen consumption (from a mean value of 3.12±0.66 to 2.85±0.63 L.min\(^{-1}\)).

In cycling, drafting effect is also experienced by the triathletes. Energy expenditure is correlated with the drag that the cyclist has to overcome during displacement. On the other hand, this depends on the effects of the gravity and the air resistance (di Prampero et al., 1979). Air resistance, and consequently energy expenditure, is reduced by drafting behind another cyclist.
or a group of cyclists. It was evidenced that drafting behind only a leader or a group of cyclists lowered VO₂, heart rate and blood lactate concentration (Hausswirth et al., 1999). It can also be speculated that weaker athletes can utilize this drafting effect to achieve better performances. Another important parameter usually assessed in cycling is the pedaling cadence. Despite the scarce literature in this matter, it has been observed that pedaling cadence used by triathletes is above 80 RPM (Hausswirth et al., 1999), close to optimal cadence suggested (90 RPM).

After cycling, the athletes have to complete the running distance. This involves some challenges, since the triathletes have to run after having already performed two different sports and have to manage the resulting energy expenditure. Triathletes typically experience a decrease in running economy when running after cycling compared to isolated running (Hausswirth et al., 1997). However, this is related to competitive level. Better triathletes exhibit less impairment in running economy than their lesser performing counterparts (Millet et al., 2000b).

**Subsequent effects of each discipline**

Millet and Vleck (2000) suggested that the ability to optimally link each discipline (or triathlon segment) is important to the success of the triathlete. Therefore, it is fundamental to know and understand the transitions between sections and the effects of each discipline on the subsequent one.

The transitions between swimming and cycling and between cycling and running correspond to less than 1.3 percent of the overall race time (Millet and Vleck, 2000). Regarding their effect on overall performance, the first transition seems to be negligible. Nevertheless, triathletes can best improve the swimming–to-bicycle change by practicing and developing the techniques involved in equipment changeover (Borchers and Buckenmeyer, 1987). Although the importance of the second transition is unclear, it is known that biomechanical, physiological and sensorial adaptations are required for the cycle–to-run transition (Millet and Vleck, 2000). Leaving their bicycle, taking off their helmet and putting on their running shoes takes about eight seconds and the higher the athlete is placed after that, the greater the importance for finishing position (Millet and Vleck, 2000).

Cycling could be influenced by the previous swimming performance. Energy saving by drafting while swimming can be used as an advantage in later phases of the competition. This could result in improvements in pedaling technique and efficiency during cycling (Delextrat et al., 2003). When comparing cycling performance after drafting swimming, Delextrat et al. (2005) observed a lower pedal cadence in association with a higher apparent gross efficiency and greater torque production. Swimming intensity affects the physiology and biomechanics of subsequent cycling and total triathlon performance. Although it is possible that long-course triathlon could not experience these effects, as the race duration decreases, swimming intensity above a given threshold can negatively affect subsequent cycling and running (Peeling and Landers, 2009). Reducing swimming intensity to values of 80–95 percent of the maximum leads the athletes to better overall performance results (Peeling et al., 2005). However, they should be cautious, since the swimming section has great importance in the final triathlon result (Landers et al., 2008).

As shown, previous swimming can affect cycling performance, but it also appears that running could be more affected by previous cycling. Cycling exercise is predominantly concentric, in contrast to running, which involves largely eccentric muscle contractions (or stretching contraction cycles – CAE movements). It seems that, in the first moments after transition, the biomechanics of running during a triathlon is quite different from the biomechanics of running performed in isolation. Nevertheless, the current literature has found no differences in running biomechanics after cycling (Hue et al., 1998). Regarding the energy cost of running
at the end of a triathlon event, energy cost is significantly higher when compared to isolated running (Hausswirth et al., 1997; Hue et al., 1998). Negative changes in running performance can occur when preceded by high-intensity cycling. However, these effects are dependent on the level of the athlete, being greater for recreational triathletes than for professional ones (Millet et al., 2000b; Millet and Bentley, 2004). Professional triathletes are well trained and are able to maintain higher relative intensity during the cycling stage, causing minor changes in subsequent exercise. Specific training of cycle–run repetitions, at high intensity, can improve the efficiency of running after cycling (Hue et al., 2002). The drafting within the cycling section is an opportunity for the triathlete to reduce intensity and save energy. This metabolic saving has been shown to influence subsequent running performance (Hausswirth et al., 1999, 2001.) Under these conditions, Hausswirth et al. (1999) found an improvement of 4 percent in running performance. At the same time, running time at 85 percent of maximal velocity was significantly increased by adopting a slow cadence (74 RPM) for the final minutes of a 30-minute cycling bout, when compared to a freely chosen cadence or even high cadence (Vercruyssen et al., 2005). These findings suggest that triathletes should use lower pedal cadence at the end of the cycling stage, in order to get more benefits during running performance.

Concluding remarks

During this chapter, the authors have attempted to present different approaches to monitoring performance, considering the role of performance indicators in individual, closed and cyclic sports. Similar characteristics exist between swimming, running, cycling and triathlon but there are also differences between each sport. Performance in these sports is related to biomechanical and physiological aspects. Coaches and athletes should consider kinematics, kinetics, neuromuscular analysis, anthropometrics, aerobic and anaerobic performance, energy cost and efficiency to enhance sports performance. An important focus was carried out to present practical implications for sports performance using scientific evidence to monitor and evaluate the training process.

Moreover, the authors attempted to make some contribution to the dissemination of the main results, stimulating young researchers in the fulfillment of the existing gap between sports science and mainstream sciences and also to bridge the gap between theory and practice.

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