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Critical Evaluation of Oxygen Uptake Assessment in Swimming

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Abstract

Swimming has become one important area of sport science research since the 1970s, with the bioenergetical factors assuming a fundamental performance-influencing role. The purpose of this study is to conduct a critical evaluation of the literature concerning the oxygen uptake (VO_2) assessment in swimming, by describing the equipment and methods used and emphasizing the recent works conducted in ecological conditions. Particularly in swimming, due to the inherent technical constraints imposed by swimming in a water environment, assessment of VO_{2max} was accomplished only in the 1960s. Later, the development of automated portable measurement devices allowed VO_{2max} to be assessed more effortless, even in ecological swimming conditions, but few studies have been conducted in swimming pool conditions with portable breath-by-breath telemetric systems. An inverse relationship exists between the velocity corresponding to VO_{2max} and the time a swimmer can sustain it at this velocity. The energy cost of swimming varies according to its association with velocity variability. As, in the end, the supply of oxygen (which limitation may be due to central - O_2 delivery and transportation to the working muscles - or peripheral factors – O_2 diffusion and utilization in the muscles) is one of the critical factors that determine swimming performance, VO_2 kinetics and its maximal values are critical in understanding swimmers' behaviour in competition and for develop efficient training programs.

Key words: Oxygen uptake assessment, direct VO_2 measurement, free swimming

Introduction

In the 1920s a sustained period of research in human exercise physiology emerged, and since then, one of the major topics has been the energetics of human locomotion and its contribution to athletic performance. Among other limits, the assessment of oxygen uptake (VO_2) for a better understanding of human bioenergetics is a key point focus of contemporary research in sport science. To better understand the basis of exercise physiology underpinning sports performance some historical details will follow.

In the late 1700s, Priestly and Scheele, independently, discovered the O_2, and Lavoisier measured VO_2 during exercise by quantifying the decrease in O_2 in a chamber when a living animal was sealed within (DiMenna & Jones, 2009). Several decades later, in 1913, Amar assessed the effect of cycling ergometer exercise by analysing samples of expired air. Hill and Meyerhof, in 1922, discovered that the contracting muscle of a frog yielded a fast production of heat on the initial contraction, and a slow production later. Concurrently, Hill and Lupton in 1922 proposed the concept of maximal oxygen uptake (VO_{2max}) during exercise in humans (Hale, 2008). Since then, VO_{2max} assessment has been conducted primarily on laboratory-based treadmill running and cycle ergometry (Hale, 2008), but there has been a growing interest in its assessment using a variety of portable and laboratory equipment in other sports.

VO_2 uptake research in swimming was very scarce during the first half of the 20th century. Liljestrand & Lindhard (1920) collected expired air and other physiological parameters (e.g. blood pressure and cardiac output) in a subject swimming freely in a lake. Karpovich & Le Maistre (1940) studied the breaststroke, and later, Karpovich & Millman (1944) investigated five swimming techniques (front crawl, inverted crawl, side, breaststroke and butterfly), in an indoor swimming pool; however, none of these early studies were conducted in ecological/ real swimming conditions and/or used trained swimmers performing at (or near) competition paces. As there are some differences in swimmers' bioenergetic and biomechanical characteristics when comparing swimming pool conditions and swimming flume (or other non-conventional methodologies as tethered swimming (Karpovich & Millman, 1944), different swimming levels (Libicz et al., 2005; Thompson et al., 2004), and sub-maximal and maximal velocities (Fernandes et al., 2006) it was expected that an underestimation of certain physiological limits, such as VO_{2max}.

The goal of competitive swimming is to obtain the fastest velocity during a race (v_{max}), it depends on the swimmers maximal metabolic expenditure ($E_{tot\text{-}max}$), and their energy cost of locomotion (C):

$$v_{max} = E_{tot\text{-}max} / C \qquad (1)$$

where, $E_{tot\text{-}max}$ can be computed based on measures/estimates of the aerobic and anaerobic energy contributions, and C is the amount of metabolic energy spent to cover one unit of distance. This metabolic energy depends on the mechanical efficiency (η_m), the propelling efficiency (η_p) and the mechanical work to overcome hydrodynamic resistance (W_d):

$$C = W_d / (\eta_p \times \eta_m) \qquad (2)$$

Some studies have examined W_d by towing a passive swimmer (Capelli et al., 1998) as well during swimming (Di Prampero et al., 1974). Similarly, methods have been developed to determine the ηm and ηp (Toussaint et al., 1988), but these methodologies have known technical limitations and are controversial. Thus, to understand the energetics of swimming, measurements of the $E_{tot\text{-}max}$ and C are the primary variables of interest. However, swimming measurements of aerobic and anaerobic pathways during swimming also have limitations imposed by the aquatic environment.

The aim of the review current study is to conduct a systematic review of the VO_2 assessment in swimming, including historic methods, but also evidencing and detailing studies that conducted VO_2 measurements in ecologic conditions. Complementarily, new perspectives and areas of study will be addressed. For this purpose, relevant literature on VO_2 consumption in swimming was located via computer-generated citations: during December 2012, two online computer searches on PubMedTM and ScopusTM databases, and on the books of the International Symposiums on Biomechanics and Medicine in Swimming, were conducted to locate published research on VO_2 consumption. The key words used to locate relevant studies were “oxygen consumption”, “maximal oxygen uptake”, “aerobic capacity” and “swimming”. Initially, all the articles obtained were selected by title; then, some of them were discarded after analyzing the abstract (excluding studies conducted exclusively on triathletes, open water swimmers, water polo players, fin swimmers, divers and animals). Finally, an integral reading of the remaining studies was conducted, and those who were deemed not within the scope of the present review were also excluded.

Methods of VO_2 assessment in swimming

Cardio-respiratory limits have been traditionally assessed to study the energetics of many individual sports including swimming. However, VO_2 is difficult to measure due to technical constrains imposed by the swimming pool and the aquatic environment (Toussaint et al., 1988). Until the early 1960s, swimming research was limited by the availability of technology, particularly the inability to follow the swimmer along the pool, the tightness of the equipment, and the drag associated with the respiratory valve system used to collect expired gas. In more recent years, research has progressed as technology has envolved, and new methods have been used to assess VO_2 in ecologic/ real swimming conditions, allowing more reliable and valid results.

Standard Open Circuit Methods: the Douglas Bag

In 1911, Douglas invented the rubber-lined canvas bags for collecting expired air that allowed assessing VO_2 and CO_2 at rest and during running and cycling exercise (DiMenna & Jones, 2009; Hale, 2008). Nowadays, the Douglas bag gas exchange analysis is still considered the gold standard for VO_2 assessment (DiMenna & Jones, 2009), but in swimming this method has several limitations, particularly on handling the bags, its permeability to the external air, and its posterior retrospective analysis determination of the relative CO_2 and O_2 concentrations (Bassett et al., 2001). In addition, to improve accuracy, some full breathing cycles are preferred, but, in a swimming pool setting, breathing cycle phases are not often counted. Hence, this method only allows determining the average VO_2 values during the period of collection chosen.

Furthermore, the Douglas bag method is difficult to conduct when swimming up and down the pool and turning at each end, as the hoses and valves pose limitations to the swimmer’s technique and collection times. Thus, to overcome this difficulty, many investigators preferentially applied by collecting consecutive samples of expired air at the end of the swim (for the first 8, 20 or 40 s of the recovery period), with the VO_2 recovery onset obtain by backward extrapolating the O_2 recovery curve. It is assumed that these values represent the VO_2 of actually preceding swimming.

The 20 s recovery gas sample was firstly used by Di Prampero et al. (1976) in speed skating, but only for two subjects performing under steady state intensity. Later, this method was shown to be valid and reproducible in treadmill cycling, treadmill testing and indoor track running (Léger et al., 1980). In addition, Montpetit et al. (1981) used the backward extrapolation method to compare VO_2 values during free swimming and uphill treadmill running. Moreover, Lavoie et al. (1983) and Costill et al. (1985) showed that VO_2 measures obtained during maximal and sub-maximal tethered and free swimming could be predicted accurately from a 20 s recovery gas sample, providing and easy and reliable in-water VO_2 assessment. In fact, a high correlation between VO_2 values collected during swimming with those estimated through backward extrapolation was observed (r=0.92). These investigators lead to the conclusion that one single sample of expired air in the first 20 s of recovery period might was needed for VO_2 prediction during a maximal or sub-maximal effort (Costill et al., 1985). Conversely, it was reported that backward extrapolation method overestimates swimming VO_2, and, although being fairly relatively easy to apply in swimming, it has several sources of errors (Lavoie et al., 1983): (i) the time necessary for the swimmer to take out the mouth piece; (ii) the high possibility of leaks; (iii) the breath-by-breath analysis required has many potential errors; and (iv) the logarithmic back extrapolation requires that the VO_2 vs. time curve fits the logarithmic model, which is often not the case.

Measuring Devices

Although the Douglas bag method has been as the "gold standard" for gas exchange measurements for over a century, the need for faster and more efficient techniques that could be used during actual swimming lead to the development of fully-automated gas analysis systems. These apparatus accurately determine CO_2 and O_2 concentrations, and are used together in combination with gas flow meter recording in real time, allowing the calculation of VCO_2 and VO_2 using standard equations. The type of gas analysers vary in different laboratories and investigations, depending on size, price and principle of measurement.

Initially, gas analysing systems used a computerized metabolic system fitted with a mixing chamber (e.g. Sensormedics 2900 oxymeter, USA) measuring mixed dead space and alveolar gases (representative of the mixed expired gas) and giving time averaged values for respiratory variables (Bassett et al., 2001). This system was not originally used in a swimming pool, under ecologic/ real swimming conditions, but in a swimming flume (Holmér & Haglund, 1978), or in a circular pool (Pendergast et al., 2003). Although a flume allows setting the swim pace, the hydrodynamic resistance is probably not the same as in free swimming (Holmér & Haglund, 1978), as there is turbulent water flow (and not laminar) that likely affects how swimmers apply their force, which consequently, will influence their technique and VO_2. The VO_{2max} during free and flume swimming was seen to be highly correlated (Holmer et al., 1974), but it was also reported that swimming flumes may influence the VO_{2max}, the corresponding velocity at VO_{2max} (vVO_{2max}) and the time to exhaustion at vVO_{2max} (Fernandes et al., 2003).

Another limitation associated with the gas exchange assessment in a swimming flume deals with the instrumentation used as the valve and the connecting tube usually increase drag, and possibly leading to a change of body position during swimming may occur. Nonetheless, it use of the connecting tube allow standardization of procedures, and the evaluation of a swimmer's energetics more continuously for a long time (Bonen et al., 1980). Complementarily, determinations of VO_{2max} have also been performed during tethered swimming (Dixon & Faulkner, 1971; Magel & Faulkner, 1967), and although comparisons between this method and free swimming are difficult (due to the differences in body position and hydrodynamics), high correlations (r=0.90) were reported in college swimmers (Dixon & Faulkner, 1971; Magel & Faulkner, 1967).

In the first initial attempts to implement VO_2 measurement in ecologic/ real swimming conditions, systems were adapted from swimming flume and tethered swimming, and the apparatus were carried on a *chariot* along the side of the pool, accompanying the swimmer (Vilas-Boas, 1993). Over recent years, to overcome the weight of the oxymeter and the requirement of the research to push this apparatus, technological advances have resulted in portable, lightweight and automated metabolic gas analysis systems, which are widespread internationally, mostly using breath-by-breath analysis (e.g. $K4b^2$, Cosmed, Italy). The main advantage of these systems is the rapid sampling frequency, enabling the monitoring of changes in VO_2 and VCO_2 in short time intervals, and allowing breath-by-breath data collection. Furthermore, a more comprehensive examination of changes in VO_2 is possible, comparing to measurements systems with lower sampling frequencies (Astorino, 2009). However, the breath-by-breath gas acquisition can induce a significant variability of the VO_2 values acquired, not being clear what the optimal sampling frequency to use when assessing respiratory limits (Sousa et al., 2010).

Swimming valves and respiratory systems

In the early 1930s, Hans Rudolph designed and built respiratory valves specifically for use in pulmonary function studies with humans and animals. These were later adapted for using during free swimming; however, by increasing the external power required for the swimmer (due to the additional hydrodynamic drag), they compromised the validity of the velocity and VO_2 measurements. To overcome this constraint, Toussaint et al. (1987) developed a low-drag respiratory valve specifically designed for VO_2 measurements during swimming, designed so that the inspiration and expiration tubes were mounted in line and passed vertically over the subject's head; wit forward extended head area, this equipment did not add significantly to the total drag of the swimmer, enabling valid measurements of VO_2 and metabolic power output. Later, Dal Monte et al. (1994) proposed a new respiratory valve system, in which gas collection tubes were aerodynamically designed, reducing even more the swimmer's drag.

The Toussaint's valve was initially adapted to Douglas bags, and later was used for direct VO_2 measurements (Vilas-Boas, 1993). At a later stage, the valve was rebuilt enabling breath-by-breath data collection with a portable system in laboratory conditions (Keskinen et al., 2000, 2003). Although its validation was conducted in dry land conditions (by comparing it values with derived with a standard face breathing mask), some systematic differences were reported and remained unclear (Keskinen et al., 2003). This system was also used in swimming pool conditions by Rodríguez et al. (2001), proving to be a feasible method for measuring respiratory exchange responses at increasing speeds during free swimming. By assessing the validity of two models of a modified swimming snorkel of a small and large volume, another investigation indicated that both small and large volumes snorkels were valid devices for measuring breath-by-breath gas exchange limits across a wide physiological range (Rodríguez et al., 2008).

Despite producing a closer approach to training and competition conditions, the gas analysis measurements in free swimming conditions, still has some technical challenges, particularly the impossibility of implementation with water starts and allowing turns, and the inexistence of a proper underwater gliding phase, as normally used; however, and despite these limitations, enables gas analysis which can provide a more reliable and representative assessment of the cardio respiratory limits during swimming. To provide a better understanding of the studies conducted in this thematic, an overview of the different methods used is presented in Table 1.

VO_2 assessment in free swimming

Initially, the main modes of exercise for establishing VO_{2max} were laboratory-based, using treadmill and cycle ergometers (Hale, 2008). These studies were fundamental in understanding basic physiological regulations, but an approach closer to competition conditions was needed. The appearance of automated portable devices for VO_2 kinetics allowed the assessment of VO_{2max} also in field conditions. This chapter describes these studies (see Table 2), aimed to assess C, VO_2 kinetics, biophysical parameters, time to exhaustion and training factors.

Energy Cost

To quantify swimming economy, one of the most relevant performance influencing factors is the assessment of C, usually determined in non ecological (not in swimming pool) conditions. Vilas-Boas & Santos (1994) and Vilas-Boas (1996) were pioneers in VO_2 measurement in free swimming, studying high-level breaststroke swimmers during a simulated swimming event, analysing and quantifying the relationship between speed fluctuations and C in three variants in breaststroke technique. They concluded that the undulating variant with overwater recovery of the arms was less economical than the underlying variant due to the higher intra-cyclic speed fluctuations. Barbosa et al. (2005a) and Barbosa et al. (2005b) reported that C increased significantly with increasing stroke rate (SR) and stroke index (SI), and that C tended to decrease with increasing stroke length (SL).

Table 2. Oxygen consumption assessment studies conducted in free swimming with direct VO_2 measurements.

Table 1. Literature review of the different studies conducted in VO_2 assessment in swimming.

Method	Authors
Studies conducted without direct VO_2 assessment in specific ergometers or in free swimming conditions	Liljestrand and Lindhard (1920), Karpovich and Le Maistre (1940), Karpovich and Millman (1944), Van Huss and Cureton (1955), Andersen (1960), Astrand and Saltin (1961), Adrian et al. (1966), Costill (1966), Costill et al. (1967), Magel and Faulkner (1967), Dixon and Faulkner (1971), Holmér (1971, 1974a, 1974b, 1974c, 1975), McCardle et al. (1971), Holmér and Astrand (1972), di Prampero et al. (1974), Nadel et al. (1974), von Dobeln and Holmér (1974), Hay et al. (1975), Magel et al. (1967), Miyashita (1975), Kemper et al. (1976), Pendergast et al. (1977), Eriksson et al. (1978), Houston et al. (1978), Kasch (1978), Kipke (1978), Klissouras and Sinning (1978), Nomura (1979), Bonen et al. (1980), Holmér and Gullstrand (1980), Montpetit et al. (1981, 1982), Cazorla and Montpetit (1983), Kemper et al. (1982), Lavoie et al. (1983), Nomura (1982), Toussaint et al. (1982), Chatard (1985), Costill et al. (1985), Lavoie et al. (1985), Stallman et al. (1986), Bouzou et al. (1987), Kohrt et al (1987), Jang et al. (1987), Montpetit et al. (1987), Toussaint et al. (1987), Cazorla and Montpetit (1988), Montpetit et al. (1988), Toussaint et al. (1988), Smith et al. (1988), Beltz et al. (1988), Toussaint (1990), van Handel et al. (1988a, 1988b), Sharp and Costill (1990), Chatard et al. (1990), Bassett et al. (1991), Ribeiro et al. (1990), Chatard et al. (1991), Rinehardt et al. (1991), Troup (1991a, 1991b), d'Acquisto et al. (1991), Capelli et al. (1992), Klentrou and Montpetit (1992), d'Acquisto et al. (1992a, 1992b), Barzeducas et al. (1992), Cappaert et al. (1992a, 1992b), Takahashi et al. (1992a, 1992b), Troup et al. (1992a, 1992b, 1992c), Chatard et al. (1992), Sardella et al. (1992), Rinehardt et al. (1992), Ogita and Tabata (1993), Ogita and Taniguchi (1995), Wakayoshi et al. (1995), Capelli et al. (1995), Wakayoshi et al. (1996), Ogita et al. (1996), Zamparo et al. (1996), Chollet et al. (1996), Alves et al. (1996), Capelli et al. (1998), Sardella et al. (1999), Cappaert (1999), Onodera et al. (1999), Termin et al. (2000), Zamparo et al. (2000), Rodriguez (2000), Demarie et al. (2001), Poujade et al. (2002), Zamparo et al. (2002), Rodríguez and Mader (2003), Kjendlie et al. (2004a, 2004b), Lafitte et al. (2004), Pendergast et al. (2005), Zamparo et al. (2005, 2006, 2008), Unnithan et al. (2009), Ratel and Poujade (2009), Mclean et al. (2010).
Studies conducted with direct VO_2 measurement in free swimming conditions	Vilas-Boas e Santos (1994), Vilas-Boas (1996), Rodríguez et al. (2003), Fernandes et al. (2003), Cardoso et al. (2003), Millet et al. (2004), Fernandes et al. (2005), Libicz et al. (2005), Bentley et al. (2005), Barbosa et al. (2005a, 2005b), Fernandes et al. (2006a, 2006b, 2006c), Morais et al. (2006), Querido et al. (2006), Barbosa et al. (2006), Ramos et al. (2006), Balonas et al. (2006), Fernandes et al. (2008), Barbosa et al. (2008), Aspenes et al. (2009), Reis et al. (2010a, 2010b), Latt et al. (2010), Seifert et al. (2010), Figueiredo et al. (2011), Sousa et al. (2011a, 2011b), Reis et al. (2011)

Study	Sample	Competitive Level	Protocol	Snorkel and Valve System	Oxymeter	VO_2 Sampling Interval	VO_{2max}/ VO_{2peak} (ml.kg^{-1}.min^{-1})
Vilas-Boas and Santos (1994)	3M, 6F swimmers	National	3x200 Br 2 Submax, 1 Max	Toussaint et al. (1987)	Sensormedics 2900	20s	69.7±4.8, M 66.3±4.7, F
Vilas-Boas (1996)	13 F swimmers	National	3x200 Br 2 Submax, 1 Max	Toussaint et al. (1987)	Sensormedics 2900	20s	?
Rodríguez et al. (2003)	10M, 4F swimmers	High Level	100, 400-m Fc Max	Keskinen et al. (2003)	K4b^2	5s	47.9±2.1and 53.3±3.3,M; 43.6±4.1 and 46.2±3.5,,F, for 100-m and 400-m, respectively
Fernandes et al. (2003)	15 M swimmers	High Level	Fc Inc Inter, Cont (@ vVO_{2max})	Toussaint et al. (1987)	Sensormedics 2900	20s	76.81±6.54 Inc Inter, 79.93 ± 6.39 Cont
Cardoso et al. (2003)	6F, 5M water polo players, triathletes, swimmers, students		Fc Inc Inter, Inc Cont	Toussaint et al. (1987)	Sensormedics 2900	20s	52.5±9.44 53.4±8.74, Inc Inter and Cont, all sample; 48.4±7.3, 49.0±6.5, Cont and Inc Inter, F; 56.2±9.6 59.0±5.5, Cont and Inc Inter, M
Millet et al. (2004)	10 M triathletes	High level	Fc Inc	Aquatrainer (Cosmed)	K4b^2	?	53.0±6.7
Fernandes et al. (2005)	11M, 12F swimmers	Experienced	Fc Inc Inter, Cont (@ vVO_{2max})	Toussaint et al. (1987)	Sensormedics 2900	20s	75.07±8.65, M 62.67±5.80, F
Libicz et al. (2005)	10 M triathletes	Trained	Fc Inc	?	K4b^2	20s	53.01±6.74, all sample
Bentley et al. (2005)	5M, 3F swimmers	National	Fc Inc 4x400m, 16x100m	Aquatrainer (Cosmed)	K4b^2	30s	55.7±5.8, 5x200; 51.2 ± 5.8, 4x400m; 52.0±8.4, 16x100m
Barbosa et al. (2005a)	3M, 1F swimmers	International	Bt Inc	Keskinen et al. (2003)	K4b^2	?	?

Barbosa et al. (2005b)	3M, 2F swimmers	National	3x200m Bt 2 Submax , 1 Max	Keskinen et al. (2003)	K4b[2]	?	?
Fernandes et al. (2006a)	10 M swimmers, triathletes and physical education students	Low Level Highly Trained	Fc Inc Inter Cont (@ vVO_{2max})	Toussaint et al. (1987)	Sensormedics 2900	20s	52.1±6.5, low level swimmers; 69.9±9.3, highly trained swimmers
Fernandes et al. (2006b)	20 M swimmers 13M, 10F swimmers	High Level	Fc Inc Inter Cont (@ vVO_{2max})	Toussaint et al. (1987)	Sensormedics 2900	20s	75.14±8.20, M; 63.94±5.49, F
Fernandes et al. (2006c)	15M, 8F swimmers	Elite	Bt, Ba, Br and Fc Inc, Cont (@ vVO_{2max})	Keskinen et al. (2003)	K4b[2]	5s	64.28±10.27, Fc; 66.78±11.40, Ba; 53.95±4.82, Bt; 63.21±8.14, Br
Morais et al. (2006)	15M, 14F swimmers	Trained	Fc Inc Inter	Toussaint et al. (1987)	Sensormedics 2900	20s	70.9±10.2, M ; 59.8±8.0, F
Querido et al. (2006)	5F, 2M swimmers	Elite	Fc Inc Inter, Cont (@ vVO_{2max})	Toussaint et al. (1987)	K4b[2]	5s	?
Barbosa et al. (2006)	8F, 18M swimmers	International	5 Br(1F, 4M), 4 Bt (1F, 3M), 5 Ba (5M) and 12 Fc (6F, 6M) Inc	Keskinen et al. (2003)	K4b[2]	?	?
Ramos et al. (2006)	7M, 3F swimmers	Elite	4 Bt (3M, 1F), 6 Br (4M, 2F) Inc, Cont (@ vVO_{2max})	Keskinen et al. (2003)	K4b[2]	?	?
Balonas et al. (2006)	12 M swimmers	Elite	Fc Inc, Cont (@vVO_{2max})	Keskinen et al. (2003)	K4b[2]	5s	?
Fernandes et al. (2008)	3M, 5F swimmers	Elite	Fc Inc, Cont (@ vVO_{2max})	Keskinen et al. (2003)	K4b[2]	5s	71.74±6.09, M; 59.80±9.97, F

Barbosa et al. (2008)	13M, 5F swimmers	Elite	Bt, Ba, Br and Fc Inc	Keskinen et al. (2003)	K4b[2]	?	?
Aspenes et al. (2009)	8M, 12F swimmers (intervention and control group)		Fc (4 Submax), 4-6 min Inc	Toussaint et al. (1987)	Corta Metamax II	10s	55.00±5.80 (intervention group) 50.00±6.20 (control group)
Reis et al. (2010a)	29 M swimmers		Fc Inter, 3 all-out tests (100, 200, 400-m)	Aquatrainer (Cosmed)	K4b[2]	20s	59.46±7.00, all sample
Reis et al. (2010b)	22 M swimmers		Br Inter, all-out test (100m, 200m)	Aquatrainer (Cosmed)	K4b[2]	20s	63.87±12.28, 100m; 66.07±13.85, 200m
Latt et al. (2010)	25 M swimmers	Adolescents	Fc 100m all-out	Rodriguez et al. (2008)	K4b[2]	10s	55.2±5.9
Seifert et al. (2010)	12 M swimmers	Elite	Fc Inc	Rodriguez et al. (2003)	K4b[2]	5s	?
Figueiredo et al. (2011)	10 M swimmers	International	Fc 200m Max	Keskinen et al. (2003)	K4b[2]	5s	?
Sousa et al. (2011a)	10 M swimmers	International	Fc 200m Max	Keskinen et al. (2003)	K4b[2]	5s	68.58±5.79
Sousa et al. (2011b)	8 M swimmers	International	Fc 200m Max	Keskinen et al. (2003)	K4b[2]	5s	69±6.3
Reis et al. (2011)	21 M swimmers	Well trained	Fc Inc Inter Fc 2x7min Max	Aquatrainer (Cosmed)	K4b[2]	30s	56±6.0

F=Female; M=Male; Max=Maximal; Submax=Submaximal; Inc=Incremental; Con=Continuous; Inter=Intermittent; Bt=Butterfly; Ba=Backstroke; Br=Breaststroke; Fc=Front Crawl; VO_{2max}= maximal oxygen uptake; VO_{2peak}=peak oxygen uptake; ?=Unknown data

Also, Barbosa et al. (2005b) showed that energy expenditure increased linearly with increasing velocity, and that the increase in C was significantly associated with the increase in intra-cycle speed variation, leading to a less efficient swimming action. Afterwards, enlarging the field of evaluation, the four competitive swimming techniques were studied by this Portuguese research group, observing the primary outcomes: (i) significant relationships between energy expenditure and intra-cycle variation, C and velocity (Barbosa et al., 2005a); (ii) that front crawl was the most economic technique, followed by backstroke, butterfly, and breaststroke (Barbosa et al., 2006); and (iii) the manipulation of the SR and SL might be one of the factors through which energy cost can be altered for a given velocity (Barbosa et al., 2008). As competitive distances vary in swimming, Seifert et al. (2010) studied the effect of swimming speciality (sprinters vs. long distance swimmers) in C (and in motor organization), observing that both groups had an increase in C of swimming with increasing velocity. For the same relative intensity, sprinters swam slower, showed a greater change in the arm coordination, and their swimming economy was lower compared to the long distance swimmers.

VO_2 Kinetics

The study of VO_2 kinetics is the study of the physiological mechanisms responsible for the dynamic VO_2 response to exercise and its subsequent recovery. Several studies have explored VO_2 swimming kinetics in laboratory and field settings, Rodríguez et al. (2003) by connecting the swimming snorkel to a telemetric portable gas analyser, were the first to investigate VO_2 kinetics during 100 m and 400 m maximal swims. VO_{2peak} was significantly correlated with speed, in both distances, proving to be a good predictor of swimming performance. The VO_2 kinetics was faster during the 100 m compared to the 400 m, demonstrating the relationship between VO_2 kinetics and swimming intensity. The result is contrary to studies reported in other cyclic sports (running and cycling) who stated that VO_2 kinetics remains remarkably constant as exercise intensity increases. Millet et al. (2004) compared VO_2 kinetics in cycling, arm cracking and swimming. The VO_{2peak} was higher in cycling, followed by arm cracking and swimming. However, VO_2 kinetics was slower in swimming, but there was similar amplitude of the VO_2 slow component in all three exercise modes. Being this the first study to compare the VO_2 kinetics within different exercise modes where swimming was one of the sports considered, comparisons with previous literature is scarce. Comparing different methods of assessment of the VO_2 slow component, Querido et al. (2006) reported that the utilization of the second minute of exercise for the estimation of its amplitude seemed to be a reasonable compromise when testing at vVO_{2max}, contrary to previous reports in swimming where the third minute of exercise was used. Reis et al. (2010b) investigated this relationship in front crawl swimming, concluding that the absolute accumulated oxygen deficit error in the all-out bouts increased concomitantly with the distance. The relative error for its estimation was much lower in the 100 m event compared to the 200 m and 400 m. Later, the relationships between physiological limits and swimming performance in breaststroke were established (Reis et al., 2010a), concluding that testing with direct VO_2 measurement and blood lactate assessment clearly provides insights into the performance ability of breaststroke swimmers, using peak VO_2 and sub-maximal and supra-maximal blood lactate measurements. Sousa et al. (2011b) characterized the VO_2 kinetics in the extreme intensity domain, during a maximal 200 m front crawl event, showing that the VO_2 kinetics response started with a sudden and exponential increase in VO_2, with no slow component. Sousa et al. (2011a) also studied the VO_2 off-kinetics in the same intensity, reporting an asymmetry between the on- and off kinetic limits, although both periods were best characterized by a single exponential regression model. Also Reis et al. (2011) characterized VO_2 kinetics, but in the heavy intensity domain, reporting that a faster VO_2 kinetics allowed higher aerobic power outputs, and that the slow component is lower in swimmers with higher ventilatory thresholds.

Relationship of Metabolic and other Biophysical Parameters
As described in the introduction, other factors influence swimming performance and VO_2. Despite the fact that the importance of the study of Biophysics in sports is nowadays well accepted, there is yet a lack of research trying to understand the relationships established between the bioenergetical and biomechanical variables in swimming. In this sense, Lätt et al. (2010) analysed the relationships between the 100 m front crawl swimming event and biomechanical, anthropometrical and physiological limits. Results indicated that biomechanical factors (90.3%) explained most of the performance variability, followed by anthropometrical (45.8%) and physiological (45.2%) ones. Using also an integrative approach (joining biomechanical and physiological variables), and despite not having given percentages relating to any of the factors, Figueiredo et al. (2011) investigated the 200 m front crawl. It was stated that the physiological partial contributions were 65.9%, 13.6% and 20.4%, for the aerobic, anaerobic lactic and anaerobic alactic systems, respectively. Moreover, and as it could be expected on biomechanical theoretical basis, fatigue developed along the 200 m since SR increased and SL and efficiency decreased.

Time Limit
The time to exhaustion at vVO_{2max} (Tlim-100%VO_{2max}) has been considered a relevant parameter as important as the VO_{2max}. Although its study only started in the last decade, investigations already were made on elite swimmers analyzing differences (Fernandes et al., 2003); in both genders (Fernandes et al., 2005); in two performance levels (Libicz et al., 2005); with biomechanical factors in the front crawl technique (Fernandes et al., 2006b); in all four competitive strokes (Fernandes et al., 2006a); with biomechanical factors in breaststroke and butterfly techniques (Ramos et al., 2006); regarding intra cycle variation of velocity in all competitive strokes (Balonas et al., 2006) and regarding ventilatory threshold (Morais et al., 2006). The primary outcomes showed an inverse relationship between: Tlim-100%VO_{2max} and vVO_{2max} (Fernandes et al., 2003; Fernandes et al., 2006a; Fernandes et al., 2008; Libicz et al., 2005); Tlim-100%VO_{2max} and energy expenditure for the entire group and for each gender (Fernandes et al., 2005); Tlim-100%VO_{2max} and SR in front crawl, butterfly and breaststroke techniques (Fernandes et al., 2006b; Ramos et al., 2006); Tlim-100%VO_{2max} and the velocity of anaerobic threshold (Fernandes et al., 2006a; Fernandes et al., 2008); Tlim-100%VO_{2max} and intra cycle variation of velocity in the front crawl and backstroke techniques (Balonas et al., 2006) and Tlim-100%VO_{2max} and body surface area and lactate production (Fernandes et al., 2008). Also the results of the studies reported direct relationships between: Tlim-100%VO_{2max} and the VO_2 slow component (Fernandes et al., 2003; Fernandes et al., 2008); vVO_{2max} and C (Fernandes et al., 2008; Libicz et al., 2005); Tlim-100%VO_{2max} and SL and SI in front crawl, butterfly and breaststroke techniques (Fernandes et al., 2006b; Ramos et al., 2006) and Tlim-100%VO_{2max} and intra cycle variation of velocity in the butterfly and breaststroke techniques (Balonas et al., 2006). Despite

the previously described results, this thematic is still scarcely studied, and as a take-home message, it has not yet been related with the intra-cyclic variation of the horizontal velocity of the centre of mass and with the distribution of the percentage of energy contribution from each energy system.

Training factors

The VO_{2max} thematic has also been studied in order to improve some practical issues in swimming training. In 2003, Cardoso et al. (2003) compared two incremental protocols (continuous and intermittent) for VO_{2max} and vVO_{2max} assessment. Both protocols were suitable for its assessment, since no significant differences regarding ventilatory parameters existed between each. Libicz et al. (2005) examined two different types of interval training sets and reported that swimming sets of the same overall time duration at vVO_{2max}, but with different work-interval durations, leads to the same VO_{2peak} values.

Continuing this thematic array, Bentley et al. (2005) conducted a study with the purpose to determine the time sustained near VO_{2max} in two interval training swimming sessions: 4x400 m and 16x100 m, concluding that the different work interval duration led to similar VO_2 and heart rate response. Aspenes et al. (2009) went on to study the impact of a combined intervention (maximal strength and high aerobic intensity interval endurance training) in competitive swimmers. Dealing with two different groups, the authors concluded that the strength training group improved land strength, tethered swimming force and 400 m freestyle performance more than the control group. The progress in the 400 m performance was correlated (r=-0.97) with the improvement of tethered swimming force, but no change occurred in SL, SR, performance in 50 m or 100 m, swimming economy or VO_{2peak} during swimming.

Conclusions

The measurement of VO_2 during sporting activities goes back to the late 19th century, and was driven by simple curiosity and the desire to advance knowledge. Over time, it VO_2 measurement has progressed to the point where it has become more effortless practical and relevant to real swimming conditions. However, there are few studies attempting to assess VO_{2max} on elite swimmers in real swimming pool conditions (and not in treadmill running or ergometer cycling) and through direct measurements of VO_2. So, more research to be conducted in the future in ecological competition conditions is needed in the future, to achieve better advices guidelines for coaches and swimmers, regarding correct training diagnosis and training intensities prescription.

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