Review

Monitoring oxygen uptake, blood lactate and heart rate in swimmers with physical impairments: A systematic review

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Abstract: Physiological parameters give an indication of the potential swimming performance. Studies regarding swimmers with impairments which gather information on physiological parameters are scarce. The aim of this study was to summarize the results of studies involving oxygen uptake, blood lactate and heart rate in swimming protocols for swimmers with physical impairments. A comprehensive search of the literature was performed on PubMed, EMBASE, Web of Science and EBSCO for complete studies between database inception and May 22nd, 2023. Ten studies (n = 142) fulfilled the inclusion criteria (including swimmers with physical impairments that monitor oxygen uptake, blood lactate and heart rate responses). A numerical summary and a narrative description of the results in relation to the research eligibility criteria were summarized. The risk of bias was assessed by Quality Assessment Checklist. In swimming protocols, swimmers with a lower functional impact of the impairment to perform sport-specific tasks showed higher oxygen uptake and blood lactate than those with a higher impact (6 studies, n = 79). The highest concentrations of blood lactate were reached in maximal anaerobic tests, followed by maximal aerobic tests (7 studies, n = 98). The relative heart rate was close to 90% in most cases (8 studies, n = 83). The studies also showed great variability in the physiological parameters concerning the categories or classifications of swimmers with physical impairments. The oxygen uptake, blood lactate concentration and relative heart rate assessments should consider functionalities and absences according to specific morphophysiological impairment.

Keywords: swimming; physiological; performance; disability

Introduction

Physiological parameters are determinants of performance in competitive swimming (Morouço et al., 2014). Oxygen uptake (VO_2), blood lactate concentration ($[La^-]^b$), and heart rate (HR) are standard parameters to be monitored (Barbosa et al., 2010; Pelarigo et al., 2017b; Toubekis & Tokmakidis, 2013). Among the physiological parameters of performance, in order of importance, coaches and competitive swimmers can benefit from the ability to maintain a high percentage of maximal oxygen uptake (VO_{2max}) (gold-standard) over a long period, to maintain a certain rhythm during sets of repetitions when associated with the intensity of swimming, and to improve the recovery after several repetitions during training (Zacca et al., 2019). Assessments of the $[La^-]^b$ are often used to avoid training load irregularities, to adjust the pace of aerobic endurance training, and to assess the anaerobic energetic capacity of swimmers (Sousa et al., 2014). The percentage of maximal HR (%HRmax) and maximal heart rate (HRmax) can be used to monitor and prescribe training intensity as the most common secondary method, due to fast increases in HR through fast increase in oxygen delivery to muscle activity and in the reduction of peripheral fatigue (Amann & Calbet, 2008; Psycharakis, 2011).

Swimmers with physical impairments are grouped into ten Sport Classes (S1 to S10) that rank the highest to smallest impact of the disability for carrying out certain specific sport tasks (International Paralympic Committee, 2018). These swimming classes are heterogeneous concerning the impairment type, for example Sport Class S4 includes swimmers with motor sensory polyneuropathy (injury and malfunctioning of the nerves of the feet and legs that can also affect the thighs and arms); complete or incomplete spinal cord injuries; cerebral palsy, with severe diplegia or severe dysmelia of three limbs; or arthrogryposis affecting four limbs, with fair propulsion from upper limbs (International Paralympic Committee [IPC] Explanatory guide to Paralympic classification in Paralympic summer sports, 2015).

Functional limitations and mobility restrictions, common in swimmers with impairments, influence the magnitude of physiological responses (Garatachea et al., 2006; Mujika et al., 2015). The physical characteristics of Paralympic swimmers, related to the main physiological parameters obtained in swimming tests or protocols, can therefore provide information regarding the type, cause, and effect – that is, the deficiency and its respective physiological effect on performance in swimming tests (e.g. cerebral palsy, spinal cord injuries, malformations, or amputations of the upper and lower limbs) can compromise muscle action, muscle perfusion, training load, performance, and recovery after exercise, and influence VO_2, $[La^-]^b$, and HR (DiRocco et al., 1985; Garatachea et al., 2006; Janssen et al., 2002; Saltin et al., 1998; Toubekis & Tokmakidis, 2013). This can contribute to a better understanding and evolution of adaptive sports, by showing, in a systematic way, how physiological responses to swimming in people with physical impairments can be altered, when compared to people without impairments. This systematic review focuses on swimmers with physical impairments who are classified into 10 Sport Classes according to the impact of an eligible impairment on the execution of specific sports tasks and activities (Sport Classes S1 to S10) (International Paralympic Committee, 2018).

It is common to note, swimmers with physical impairments have some loss of horizontal body alignment relative to the water surface, with deeper positions of the hips and lower limbs in the water, increasing drag. In addition, swimmers with physical impairments (e.g. swimmers with cerebral palsy, spinal cord injury, amputations and malformations) show the same characteristics in swimming parameters. Swimming speed (SS), stroke length (SL), and stroke rate (SR) are higher in swimmers with a lower functional impact of physical impairment to perform sport-specific tasks (Feitosa et al., 2022; Pérez-Tejero et al., 2018). The SR is more valued than the SL to achieve high SS in swimmers with upper limb physical impairments (Feitosa et al., 2022). These positions and swimming parameters during front crawl stroke impose a great propulsive force to overcome the increased drag (Capelli et al., 1995), leading to increased VO_2 (Chatard et al., 1992). $[La^-]^b$ is a product of the physiological system disability, in response to the effort of swimmers with low mobility and consequent reduction of blood flow, especially in the lower limbs (Bentley et al., 2002). Analyses of $[La^-]^b$ reflect the effort intensity (Donovan & Brooks, 1983). Complementarily, increases in sympathetic and parasympathetic activity also reflect, respectively, increases and decreases in HR (Koenig et al., 2014).

Paralympic swimming has been developing steadily over the past decades. Likewise, there is an increase in evidence-based insights on the performance and physiological response of swimmers with impairments. However, to the best of our knowledge, no reviews on the VO_2, $[La^-]^b$, and HR response of swimmers with impairments was found by the authors. The present systematic review adds information particularly focused on providing physiological responses of swimmers with physical impairments who have participated in protocols for assessing swimming performance. In addition, the physiological responses arising from performance assessment protocols for swimmers with physical impairments can provide evidence for a better understanding of performance in training and competitions (de Souza et al., 2016), bridging theory and practice, by assisting coaches in their training prescription and highlighting areas for further research. The aim of this study was to summarize the results of studies involving VO_2, $[La^-]^b$, and HR in swimming protocols for swimmers with physical impairments.

Materials and Methods

Eligibility criteria

This systematic review was carried out following the recommendations of the PRISMA Statement (Page et al., 2021). The eligibility criteria were based on the inclusion of studies recruiting swimmers with physical impairment, aiming to monitor the physiological response (any term: VO_2, $[La^-]^b$, and HR). There was no language restriction, as long as the studies had titles and abstracts in English, and full text were available studies No restrictions were applied regarding the time of publication. The exclusion criteria were: absence of information or incomplete data in articles and multiple publications in which the results were repeated – only one of these studies would be included if found. Protocols, editorials, discussion papers, and commentaries were also excluded.

Databases and search strategies

Data were gathered through searches on PubMed, EMBASE, Web of Science and EBSCO (SPORTDiscus, MEDLINE and Academic Search Premier). Completed published studies were screened between database inception and May 22nd, 2023. Reference lists of the articles found were also searched.

The search strategy used the Medical Subject Headings (MeSH) descriptors of health science subjects and term BIREME – DeCS, as well as their synonyms and combinations between the words for the following categories: population – amputees OR "disabled person" OR "disabled swimmers" OR "sports for persons with disabilities" OR "physical impairments" OR impairment; Intervention – freestyle OR "front crawl" OR swimming; outcome – aerobic OR anaerobic OR "blood lactate concentration" OR "heart rate" OR "oxygen consumption" OR "uptake oxygen" OR "peak oxygen" OR physiological OR physiology. The Boolean operators 'AND' and 'OR' were used for tracing during the searches in the electronic databases.

Selection of studies and extraction of results

The selection of the studies was carried out in two stages: 1st – reading the titles and abstracts of all the articles identified during the search strategy, independently by two researchers (WF and RC). Studies that did not provide enough details about the inclusion and exclusion criteria were selected for complete article evaluation; 2nd – the same reviewers, independently (WF and RC), assessed the full content of the articles and made their selection according to the eligibility criteria. Disagreements between reviewers were resolved by a third independent reviewer (FC). Data extraction was performed using a standardised form. Duplicates were removed with Endnote software support by manually checking the similarities in the studies, reference by reference.

Physiological outcomes

Absolute (L·mim^{-1}) VO_2 was identified in studies that demonstrated any form of collection of expired gases, by a gas analyser or metabolic cart (de Jesus et al., 2014). The $[La^-]^b$ was identified from intravenous collection, collected through the ear lobe or fingertip, represented by the highest value achieved after the effort in swimming tests (Sousa et al., 2010). The HR in beats·min^{-1} was identified in absolute values. The %HRmax was calculated from the values of the HRmax, based on the equation [208 – 0.7 × age] (Tanaka et al., 2001), minus the maximal HR of the swimming tests, split by the absolute value and multiplied by 100: [(HRmax – HR swim test)/ (HRmax)] × 100 (Wilmore & Costill, 2004).

Risk of bias assessment

The Downs and Black Quality Assessment Checklist was used to provide a score on the overall quality of the studies (Downs & Black, 1998). Higher scores represented articles with superior quality. The scores obtained were expressed as a percentage: [(total number of points achieved/total number of applicable points) × 100]. Additionally, results of the quality of the studies were also presented by the point variation obtained in the quality index and values of mean and standard deviation. Adjustments were deemed as necessary: the word ‘patient’ was changed to ‘participant’ and ‘treatment’ interpreted in the context of ‘test’, and item 27, which sought to assess whether the negative findings of the study could be due to chance, was excluded. This tool was used by two reviewers independently (WF and RC). Whenever necessary, a third reviewer (FC) was required to reconcile on the different opinions.

Data analysis

Quantitative analysis was performed based on the main characteristics of the studies, with information about: authors’ names and year of publication, data samples, and main methods with selected outcomes. A numerical summary and a narrative description of the results in relation to the research eligibility criteria were summarized. The mean (*M*) values and standard deviation (*SD*) of the results were registered when available.

Results

The search strategy returned 227 articles, of which 107 were duplicates and were removed. In the first phase of analysis, 108 studies were excluded based on the title or abstract. In the second phase, four studies were excluded after being read in full. Two complete studies were included from other sources (e.g., article in a book, and from the references of the original articles.). Ten studies were examined extensively because they matched the inclusion criteria (Figure 1).

The characteristics of the studies included are shown in Table 1. They were published between 1985 and 2021. The quality of studies ranged between 50% and 69.23% (13 to 18 points, average score for all papers: $M = 15.36$, $SD = 1.80$). The most common missing items included: probability values, items related to the invitation and the representativeness of the participants, the randomization procedures for intervention groups, intervention task, and loss of study participants. We gathered the samples from each study (overall n = 142 participants) in order to increase the evidence on the responses of the physiological parameters in swimmers with physical impairment.

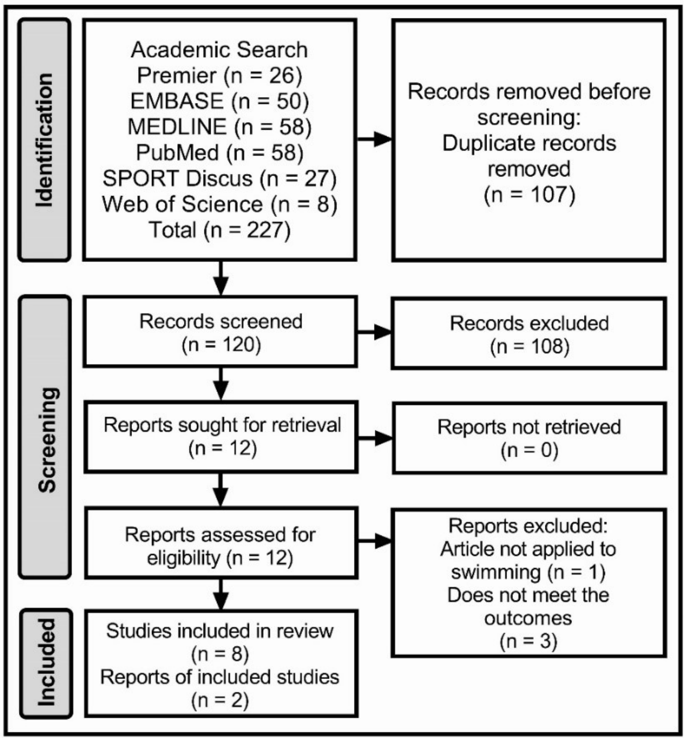

Figure 1. Flowchart of the systematic literature search.

The included studies had methodological differences regarding the protocols used to assess the physiological response: tethered swimming, 4 × 50m max; different percentage of critical swimming speed; one maximal anaerobic test (the swimmers performed the first test over a distance of 50m to 100m, according to their swimming speed), and aerobic-anaerobic test of intensities (the swimmers performed the second test over a distance of 150m to 200m, or 300m to 400m, depending on their swimming speed); an all-out 200m front-crawl stroke test; tests of increased speed (200m, 400m or 800m tests [swum at a steps of progressively speed at 50m, 100m or 200m, depending on physical impairment]); and 21min aerobic, 5 × 200m, 6 × 300m, 7 × 200m. A high variability of the participants' classifications across studies was also noted.

Oxygen uptake

The selected physiological variables and sport classes (or physical impairment) were examined (Table 1). VO_2 (n = 79) was assessed in six studies. The VO_2 obtained in different swimming protocols were higher for most swimmers with less impact of a physical impairment on their ability to perform the specific activities requested. In most cases, the VO_2 results ranged from the highest to the lowest values of the sport classes S10 to S1 .

In the tethered swimming test, the VO_2 was elevated according to the spinal cord injury level in male swimmers (highest spinal cord injury in C7 to less spinal cord injury in T12 – increasing VO_2 from 1.06 to 2.6 L·min^{-1}, n = 4; DiRocco et al., 1985). Two other female swimmers from the tethered swimming study had spinal cord injury due to the poliomyelitis virus and had VO_2 of 0.76 to 1.18 L·min^{-1} (DiRocco et al., 1985). No similar study with the tethered swimming test was found for swimmers with other physical impairments. Analysis of VO_2 in the 200m front-crawl stroke test was also found (VO_2; M = 3.1, SD = 0.6 L·min^{-1} for males; and M = 1.9, SD = 0.3 L·min^{-1} for females, sport classes S5, S7 to S10; Ongaratto et al., 2021).

During the swimming tests of 200m, 400m and 800m freestyle swim (depending on the disability), at progressively increasing speed until exhaustion, the following results were obtained for swimmers in sporting classes S1 and S2, male VO_2; M = 2.2, SD = 0.1 L·min^{-1}, female VO_2; = *M* 1.5, *SD* = 0.1 $L \cdot min^{-1}$ and swimmers in sporting classes S3 and S4, male VO_2; *M* = 3.2, *SD* = 0.7 $L \cdot min^{-1}$, female VO_2; *M* = 2.1, *SD* = 0.3 $L \cdot min^{-1}$ (Chatard et al., 1992).

The Sport Classes S5 and S6 had similar VO_2 in tests with increased swimming speed (7 × 200m, 6 × 300m) with VO_2 values ranging from 3.2 to 3.9 $L \cdot min^{-1}$ for males and 2.4 $L \cdot min^{-1}$ for females (de Souza et al., 2016; Rodrigues Junior et al., 2016). The sport classes S5–S9, presented increased values for VO2 from the lowest sport classes to the highest sport classes in the incremental speed test (de Souza et al., 2016; Feitosa et al., 2019; Rodrigues Junior et al., 2016).

Blood lactate

The $[La^-]^b$ was assessed in seven studies (n = 98). The $[La^-]^b$ obtained in different swimming protocols were higher for most swimmers with less impact of a physical impairment (higher results from sport classes S10 to S1). The $[La^-]^b$ increased when: (i) the intensity of exercise increased and (ii) activated muscle mass was increased during physical exercise (de Aymerich et al., 2010). The [La-]b was higher in the 4 × 50m max tests for sport

classes S3 or S7 ([La-]b; M = 14.35, SD = 4.08 mmol·L-1; Pelayo et al., 1995), than in the maximal anaerobic test, 50m to 100m, depending on the swimming speed of each swimmer ([La-]b; M = 11.93, SD = 0.63 mmol·L-1 for sport classes S6 to S10; de Aymerich et al., 2010) and, then by the results of the 5 × 100m or 5 × 200m for swimmers with partial or total loss of movement of the lower limbs ([La-]b; approximately 11.3 mmol·L-1; Bentley et al., 2002). The next highest values were for the aerobic swimming tests of 21 minutes of effort for sport classes S4, S5 and S7 ([La-]b; M = 10.80, SD = 3.50 mmol·L-1; Pelayo et al., 1995). In sequence, the highest values were from an aerobic-anaerobic test ([La-]b; M = 9.78, SD = 0.45 mmol·L-1 for sport classes S6 to S10) in distances from 150m to 200 m, or 300m to 400m, depending on each swimmer's swimming speed (de Aymerich et al., 2010), followed by a maximal anaerobic test ([La-]b; M = 9.52, SD = 0.81 mmol·L-1 for sport classes S1 to S5), 50m to 100m, depending on the swimming speed of each swimmer (de Aymerich et al., 2010).

In the incremental intermittent swim test (5 × 200m and 7 × 200m), the highest $[La^-]^b$ increases were from sport classes S5 to S9, with the exception of sport class S10, which reached lower blood lactate values (Feitosa et al., 2019; Rodrigues Junior et al., 2016). We also noticed increases in $[La^-]^b$ with increasing intensity in critical speed swimming tests for swimmers in Sport Classes S3-S7 (Garatachea et al., 2006).

Heart rate

Maximum HR (n = 75) was reported in eight studies. In relation to HR, the majority of swimmers with physical impairment reached values near 90% of maximum HR. Some exceptions occurred in the case of swimmers with spinal cord injury (SCI, T8 and T12), polio and swimmers who performed critical speed tests, values below 142 $beats \cdot min^{-1}$ for HR or 67% of %HR (DiRocco et al., 1985; Garatachea et al., 2006).

Table 1. Physiological outcomes of swimmers with impairment in front crawl or freestyle.

Author (year)	Quality %	Test	Level	Impairment or Sport Classes	Male	Female	Oxygen uptake (L·min⁻¹)		Peak lactate (mmol·L⁻¹)		HR·min⁻¹		% HRmax
							Mean	SD	Mean	SD	Mean	SD	
DiRocco et al. (1985)	57.6	Tethered Swimming	No info	SCI – C7	1		1.0				166		95%
				SCI - T8	1		1.8				130		51%
				SCI – T12	1		1.5				180		100%
					1		2.6				138		61%
				Polio		1	0.7				141		68%
						1	1.1				182		100%
Chatard et al. (1992)	69.2	Aerobic*	Int	S1 and S2	8		2.2	0.1					
						5	1.5	0.1					
				S3 and S4	6		3.2	0.7					
						4	2.1	0.3					
				S5 and S6	7		2.6	0.2					
						4	2.4	0.8					
Pelayo et al. (1995)	65.3	Aerobic 21 min	Nat	S4, S5 and S7	6	2			10.80	3.50	182	8	94%
		4 x 50m maximum	Nat and Int	S3 or S7	2	4			14.35	4.08			
Bentley et al. (2002)	53.8	5 x 100m or 5 x 200m	Int	Had partial or total loss of movement of the lower limbs	6				1.3		187	14	98%
Garatachea et al. (2006)	50.0	95% of CSS	Nat and Int	S3 – S7	8				3.3	0.9	143	18	67%
		100% of CSS**		S3 – S7	8				4.03	1.2	154	7	76%
		105% of CSS		S3 – S7	8				5.7	2.0	159	20	81%
de Aymerich et al. (2010)	57.7	One maximum anaerobic	Nat and Int	S1 – S5	10				9.52	0.81			
				S6 – S10	9				11.93	0.63			
				S1 – S5	10				7.39	0.80			

Author (year)	Quality %	Test	Level	Impairment or Sport Classes	Male	Female	Oxygen uptake (L·min^{-1})		Peak lactate (mmol·L^{-1})		HR·min^{-1}		% HRmax
							Mean	SD	Mean	SD	Mean	SD	
		Aerobic-anaerobic intensities		S6 – S10	9				9.78	0.45			
Rodrigues Junior et al. (2016)	53.8	7 x 200m	Fed	S6	1		3.2		4.40		178		92%
				S7	1		2.5		4.90		173		89%
				S8	4		2.9	4.0	5.90	1.90	179	10	93%
				S9	6		3.0	6.9	6.40	2.60	159	50	79%
				S10	1		2.1		3.60		175		90%
de Souza et al. (2016)	65.3	6 x 300m	Nat	S4	1		1.2				187		100%
				S5	1		2.0				173		92%
				S6	1		3.9				188		101%
				S7		1	2.1				180		96%
Feitosa et al. (2019)	61.5	N x 200m	Reg and Int	S5	1		2.4		9.5		161		88%
						1	1.9		3.8		128		77%
			Reg	S7	1		2.0		11.8		170		98%
			Reg and Int	S8	1		3.7		9		172		100%
						1	1.4		5.2		167		108%
			Reg, Nat and Int	S9	4		3.1		12.5	4.5	175	8	94%
						1	2.2		11.7		170		91%
			Reg	S10		1	2.1		4.9		169		98%
Ongaratto et al. (2021)	61.5	200m	Reg, Nat and Int	S5, S7 to S10	7		3.1	0.6	14.8	3.0			
						4	1.9	0.3	8.3	3.4			

Int = International; Nat = National; Fed = Federated; Reg = Regional swimmers; No info = No information; *M* = Mean; *SD* = Standard Deviation; SCI = Spinal Cord Injury; Aerobic* = 200m, 400m or 800m dependent on the level of conditioning; CSS= Critical Swimming Speed test; Class = classification of swimmers with Physical Impairments, more information see (Dummer, 1999; Sampedro et al., 2016).

Discussion

Studies on VO_2, $[La^-]^b$, and HR in swimming tests or protocols applied to swimmers with physical impairments were systematically reviewed. There are great methodological differences in swimming tests and large variability in the categories or classifications of the participants. The sample sizes of most of the studies reviewed were small. When evaluating each study individually it is possible to perceive the VO_2 is higher in sport classes with less impact of physical impairment. The $[La^-]^b$ increased when exercise intensity was higher, and also when activated muscle mass increased during exercise. The HR was close to 90% for most swimmers with impairments.

Quality of the research

The quality of the studies found in this systematic review on the physiological parameters of swimmers with physical impairments ranged from 13 to 18 points achieved (M 15.27, SD 1.68 in points). Systematic reviews with elite swimmers without impairments showed study quality indices ranging from 9 to 19 points (M 11.68, SD 2.25 points) for energetic, biomechanical, and performance parameters (Costa et al., 2012), and ranging from 8 to 19 points (M 11.04, SD 2.04 points) for physiological adaptations to training in swimming competitions (Costa et al., 2015). It is possible to notice higher means for the studies with impaired swimmers than for those without impairment. The quality of this study on the monitoring of physiological parameters in swimmers with physical impairments (points achieved ranged from M 15.27, SD 1.68) was lower than the results found in a systematic review also with swimmers with impairments (M 16.72, SD 3.01), but which addressed biomechanical parameters (Feitosa et al., 2022).

Oxygen uptake

Researchers (Chatard et al., 1992; DiRocco et al., 1985; Feitosa et al., 2019; Rodrigues Junior et al., 2016) have reported VO_{2max}, and in two studies (de Souza et al., 2016; Ongaratto et al., 2021) there was the peak oxygen uptake (VO_{2peak}). The standard and mainstream procedure assessing cardiorespiratory response in physical testing is to reach VO_{2max}. However, when VO_{2max} was not reached, following primary and secondary criteria (Howley et al., 1995), VO_{2peak} was used as a reference of the highest value of VO_2 (Sousa et al., 2011).

The methodology for VO_2 register in each swimming test was different. One of the studies (DiRocco et al., 1985) had the tethered swimming test with VO_2 collected by metabolic cart. Another had 200m, 400m or 800m protocols until exhaustion, and the respiratory gases were collected by Douglas bags (Chatard et al., 1992), which obtained average values of VO2 during the specific period and not breath-by-breath (DiMenna & Jones, 2009). VO2 was reported in incremental swimming tests (increases in swimming speed) in two studies as VO2max in 7 × 200m tests (Rodrigues Junior et al., 2016) and in different numbers of sets over the 200m distance (N × 200m), where VO2max was achieved by some swimmers at 7 × 200m, 6 × 200m, and even 5 × 200m (Feitosa et al., 2019). In two studies, VO_{2peak} was measured from 6 × 300m and 200m tests (de Souza et al., 2016; Ongaratto et al., 2021). Incremental tests are considered the gold-standard in swimming performance research (de Jesus et al., 2014), but VO_{2max} and VO_{2peak} are considered different parameters (Sousa et al., 2010). Although VO2max and VO2peak are different physiological parameters, VO2peak can be considered a valid estimate of VO2max, since swimmers with physical impairments showed VO2peak values obtained from the 200m rectangular test that were similar, concordant, and correlated with the VO2max values obtained from the incremental protocol.

The VO_2 of physically impaired swimmers is lower than that found in the literature for highly trained male swimmers without disabilities (VO_{2max}; M = 4.24, SD = 0.60 L·min^{-1}), values obtained at the end of the incremental protocols (7 × 200m; Sousa et al., 2015). Theoretically, there was an inversely proportional relationship between muscle perfusion and muscle mass involved in the action (Saltin et al., 1998), which influenced the use of oxygen by the muscles involved in dynamic exercise (Astrand & Rodahl, 1986). Thus, VO_{2max}, according to the Fick principle, is the product of maximal cardiac output and the arteriovenous oxygen difference (arterial O_2 minus venous O_2; Narang et al., 2012). As the muscular action and the ability to capture, transport and use O_2 (Joyner & Coyle, 2008) would be reduced due to limb deficiency, swimmers with impairments limbs or muscular system should have lower VO_2 than those without deficiencies.

Considering each study individually, VO2 was higher for the majority of swimmers with a lower functional impact of physical impairment to perform specific competitive swimming tasks. Swimmers with impaired arm and leg actions, such as spinal cord injuries (e.g., tetraplegia, with injury in C1 to C7, within sport classes S1-S4 and paraplegia, with injury in T1-L5, within sport classes S5-S9), execute propulsive arm movements, with limited coordination and drag produced by the lower limbs, are more affected in aerobic and anaerobic metabolic capacity, when more muscles are paralysed (Janssen et al., 2002). In this sense, the lower the VO2, the greater the functional impact of the impairment in performing specific swimming tasks. This can be noticed in swimmers with spinal cord injury in C7, T8 and T12 in tethered swimming tests (DiRocco et al., 1985), in which VO2 was also lower in swimmers with a higher functional impact of physical impairment to perform specific swimming tasks in the following increasing sequence of sport classes: S1 and S2; S3 and S4 in the aerobic test with increased velocity in 200m, 400m or 800m (Chatard et al., 1992); S4 in 6 × 300m (de Souza et al., 2016); S5 and S6 in the aerobic test (Chatard et al., 1992); S6 and S7 in 7 × 200m, 6 × 300m and N × 200m (de Souza et al., 2016; Feitosa et al., 2019; Rodrigues Junior et al., 2016). This relationship of VO_2 in people with tetraplegia and paraplegia is also maintained in well-trained athletes during the wheelchair test (VO_{2peak} 1.2 L·min^{-1} vs. VO_{2peak} 2.3 L·min^{-1} for tetraplegic vs. paraplegic, respectively; Janssen et al., 2002).

The other classifications assessed to VO2 tests (sport classes S7, S8, S9) also show that VO2 was higher when the swimmers' physical impairment had a lower functional impact on their ability to perform specific swimming tasks, maintaining a relationship with the swimmers' gender, age and body mass (de Souza et al., 2016; Feitosa et al., 2019; Rodrigues Junior et al., 2016; Staff, 2018). It was expected that the sport class S10 swimmer (participant male) with VO2max of 35.1 mL·kg–1·min–1 and [La-]b of 3.6 mmol·L–1 had VO2max higher than the other classes. But, from a qualitative perspective, this was not what happened. Thus, VO2max is expected to be higher in swimmers with less functional impact of physical impairment to perform specific swimming tasks, respecting sex and level of physical conditioning. Researchers should consider functionalities and absences according to the morphophysiological impairment of swimmers when carrying out VO2 assessments.

Blood lactate

Analysis of $[La^-]^b$ are often used to avoid irregularities in training load, to adjust the pace of aerobic resistance training (Garatachea et al., 2006; Toubekis & Tokmakidis, 2013) and to assess the swimmers' anaerobic energy capacity (Ferreira et al., 2016). The ability to maintain a high percentage of VO2max over a long time, but also to maintain a certain pace during a set of repetitions, can be achieved with the support to assess aerobic endurance indices (Bosquet et al., 2002). The main indices of aerobic resistance are (Toubekis & Tokmakidis, 2013): lactate threshold (LT); maximal lactate steady state (MLSS); onset of blood lactate accumulation (OBLA); and critical swimming speed (CSS). The identification of the LT occurs at moderate intensity in which there is equilibrium in VO2 and possibly decreasing lactate (Toubekis & Tokmakidis, 2013). LT has been determined by fixed values of 3.5 mmol·L−1 of [La-]b (Pelarigo et al., 2017a). All the results in the found studies exceed the LT intensity of 3.5 mmol·L−1, except for the 95% intensity of the CSS (Garatachea et al., 2006). CSS is recognised as the maximum speed that could be sustained without eliciting VO2max, at constant speed (Hill & Ferguson, 1999; Ribeiro et al., 2010) and is often employed by swimmers because it is not invasive (Rizzato et al., 2017). However, [La-]b concentrations above 4 mmol·L−1 are also reached by increasing the percentage intensity of the CSS (100% of CSS, [La-]b 4.03 ± 1.2 mmol·L−1 and 105% of CSS, [La-]b 5.7 ± 2.0 mmol·L−1) (Garatachea et al., 2006), as well as in other tests with speed increases where this value was exceeded, representing maximum concentrations for the test. The onset of exponential increase in mean [La-]b corresponding to intensity of 4 mmol·L−1 is understood as and corresponds to OBLA (Sjodin & Jacobs, 1981).

The results of [La-]b increasing with increasing exercise intensity (Toubekis & Tokmakidis, 2013). Increased muscle mass activation contribute to higher [La-]b, based on comparisons in which the peak blood lactate in the whole swim was higher than only arm strokes, or only the kick strokes in recreational swimmers (Ohkuwa & Itoh, 1992). The lower the sport classes in swimming, the greater the functional impacts of physical impairment on sport-specific tasks (International Paralympic Committee, 2018). The exception of the Sport Classes S5 (peak lactate ([La-]b 3.8 mmol·L−1 in incremental velocity test N × 200-m) (Feitosa et al., 2019) and Sport Classes S10 (peak lactate ([La-]b 3.6 mmol·L−1 in test N × 200-m for female swimmer) may have occurred due to lower physical capacity, reinforced by lower oxygen uptake (35.1 mL·kg−1·min−1 for male swimmer and 35.7 mL·kg-1·min−1 for female swimmer) (Feitosa et al., 2019; Rodrigues Junior et al., 2016). This was not expected for well-trained swimmers sport class S10, because sport classes S10 includes swimmers with minimal functional impacts from physical impairments to perform sport-specific tasks, such as a restriction of movement in the hip joint (International Paralympic Committee, 2015).

Furthermore, in the specific case of swimmers with physical impairment, muscle activation may be compromised in some cases due to the lower limbs' spasticity and paralysis, resulting in the need to maintain muscle activation during exercise recovery to decrease $[La^-]^b$ (Pelayo et al., 1995). Increased release of $[La^-]^b$ is caused by reduced blood flow, especially in the lower limbs during whole body movement (Secher & Volianitis, 2006). Moreover, the highest $[La^-]^b$ were collected with the maximal anaerobic lactic test (Bentley et al., 2002; Pelayo et al., 1995) and aerobic tests with increasing speed throughout the swimming test (Feitosa et al., 2019; Garatachea et al., 2006; Pelayo et al., 1995; Rodrigues Junior et al., 2016). The $[La^-]^b$ of the swimmers with physical impairments in incremental speed tests (Rodrigues Junior et al., 2016) and in the critical swimming speed (CSS) test (Garatachea et al., 2006) were lower than the results of the well-trained male swimmers without impairments (incremental protocol $[La^-]^b$ M = 7.18, SD = 2.52 mmol·L^{-1}; Sousa et al., 2014) and similar in the critical swimming speed for swimmers without impairments to 95% of the CSS; $[La^-]^b$ 3.3 mmol·L^{-1}; 100% of the CSS' $[La^-]^b$ 4.6 mmol·L^{-1} (Filipatou et al., 2006).

Intermittent incremental protocols and protocols at maximal velocity are part of the strategy for assessing the maximum capacity of swimmers (Bentley et al., 2005). In the context of intermittent incremental protocols, peak $[La^-]^b$ was reached after the end of the tests (Bentley et al., 2002; Pelayo et al., 1995; Rodrigues Junior et al., 2016). In these tests, one can find the MLSS, considered gold-standard for aerobic assessment and corresponding to the intensity that can be sustained over time without the lactate production exceeding removal of 1 mmol·L−1, with steady lactate and steady VO2 (Billat et al., 2003).

The increase in metabolic performance based on peak [La-]b reinforces the Paralympic classification, because swimmers with lower functional impact of physical impairment had better swimming performance.. The highest concentrations of $[La^-]^b$ were reached by swimmers with lower physical impairment. The muscle activation of swimmers with cerebral palsy may be compromised due to spasticity and paralysis in the lower limbs. The highest $[La^-]^b$ were reached in aerobic tests with increasing speed throughout the swimming test.

Heart rate

Trained individuals can benefit from fast increases in HR through the fastest increase in oxygen delivery to muscle activity, reducing peripheral muscle fatigue (Amann & Calbet, 2008). HR is one of the most common methods used by coaches to monitor, regulate, and prescribe training intensity, because the HRmax is directly related to VO_{2max} in the Fick equation (Psycharakis, 2011). However, the use of %HRmax instead of HRmax is recommended due to a few issues (Psycharakis, 2011): (i) HRmax is not recommended as a parameter in different levels of swimmers because swimmers at different levels can have significantly different HR values; (ii) HRmax in studies with swimmers of different ages may cause misleading in the data interpretation and difficulty in comparisons with other studies if the dispersion of ages is high; (iii) studies with swimming performance in different methods (e.g. free and tethered swimming; swimming in the pool and in flume) have limited generalisability. These issues seem to reinforce the recommendation to use %HRmax instead of HRmax, both provided in the present systematic review on monitoring physiological parameters, since the results found are from swimmers with different competitive levels, different ages, and in different tests to assess performance.

Nevertheless, the HR and %HRmax reached by swimmers with physical impairment during the swimming tests were diverse. A high %HRmax (HR > 90% [208 – 0,7 × age]) is considered a secondary factor to establish what the maximal aerobic capacity was reached (Howley et al., 1995). HR (beats·min^{-1}) was elevated for most of the tests with swimmers with physical impairments when they performed at maximum or close to maximum effort. The lowest HR was found for some swimmers with spinal cord injury (SCI, T8 and T12) and polio in the tethered swimming test (DiRocco et al., 1985) and female swimmer with hemiplegia (sport class S5) (Feitosa et al., 2019) or among swimmers who performed the CSS test (Garatachea et al., 2006). A better understanding of HR can be perceived by converting the maximum HR from absolute to relative values (%HRmax) (Psycharakis, 2011). The %HRmax relativised by age in years was close to 90% in most cases, indicating that the swimmers performed the tests close to the maximal effort (Bentley et al., 2002; Garatachea et al., 2006; Pelayo et al., 1995; Rodrigues Junior et al., 2016). The %HRmax obtained during tests with increased speed showed that swimmers with greater physical restrictions reached higher %HRmax at slower speeds, which can be explained by these swimmers having more severe functional impairments (Rodrigues Junior et al., 2016), and this was influenced by the variability of sympathetic and parasympathetic activation in training adaptations (Koenig et al., 2014).

In addition, the lowest %HRmax obtained in the short tethered swimming tests in swimmers with spinal cord injury and polio (DiRocco et al., 1985) and the CSS test (Garatachea et al., 2006) are possibly explained by the activation of the sympathetic system being slower, with a timescale of seconds, while parasympathetic effects are faster, with a timescale of milliseconds (Pluim et al., 2000). The low mobility of swimmers seems to influence the changes in %HRmax, in particular the parasympathetic vagal activity

(Melanson & Freedson, 2001). In addition, individuals with tetraplegia and loss of autonomic integrity with deficiency of the sympathetic system to the heart had substantially lower HR than athletes with other impairments (West et al., 2015). Moreover, it is important to note that HR decreases when the body was immersed in water (Town & Bradley, 1991), due to the change in haemodynamics associated with the horizontal body position in swimming (Dixon & Faulkner, 1971) and that the peak HR in training was, on average, lower than in competitions (Hullemann et al., 1975).

Swimmers with physical impairments made efforts close to the maximum. The swimmers with the greatest physical restrictions reached higher %HRmax at lower speeds and this seems to have been influenced by the variability of sympathetic and parasympathetic activation in training adaptations. Furthermore, some swimmers with spinal cord injury with deficiency of the sympathetic system to the heart had substantially lower %HRmax. The particular physiological characteristics of each eligible impairment should be considered when determining the HR of athletes with high spinal cord injuries (e.g., cervical and upper thoracic segments; DiRocco et al., 1985; Pluim et al., 2000; Simim et al., 2017). In such cases, stroke volume is reduced due to the loss of sympathetic activity below the level of the injury that does not allow blood to be redirected (Goosey-Tolfrey, 2010), in addition to the use of medications that may influence HR responses (Simim et al., 2017).

Limitations

The main limitations of this systematic review were twofold: (i) a quality analysis of observational studies required subjective adaptations in the Downs and Black Quality Assessment Checklist, even if these adaptations are common and suggested for this instrument, and (ii) there was great heterogeneity of impairments found in the sports classification and reduced number of participants in each study. We understand that there is great difficulty in selecting participants with physical impairments for the studies and, even considering the set of publications to date, it has been possible to achieve only approximations of each sport class for each outcome. The heterogeneity of the swimmers with physical impairments in the current study makes it difficult to extrapolate the results, but contributes with approximations, when there are similarities in the characteristics of these swimmers. In this way, future updates of this systematic review are necessary in similar conditions of training and competition. This would allow better guidelines for assessing the performance of swimmers with impairments.

Conclusions

The present systematic review shows that there are large methodological differences in swimming tests. The quality of the studies was mostly poorer than studies recruiting swimmers without impairments. Through this review, we also demonstrated variability in the physiological parameters concerning the sport classes of swimmers with physical impairments. However, from individual assessments within each study, VO_2 was higher in sport classes with lower impact of physical impairment. The highest concentrations of $[La^-]^b$ were reached by swimmers with lower physical impairment, among them, swimmers with cerebral palsy, possibly compromised due to spasticity and paralysis in the lower limbs. The HR was close to 90% for most swimmers with impairments. Thus, the monitoring of VO_2, $[La^-]^b$, and HR in swimmers with physical impairment should be individualized according to the potentialities presented by each swimmer, according to the protocols or tests performed.

Perspectives

We encourage coaches and physical trainers to assess the physiological responses of swimmers with impairments. When conducting VO2, [La-]b, and %HRmax assessments, researchers should consider functionalities and absences according to each swimmer's morphophysiological impairment. Monitoring adaptations in VO_2, greater tolerance to $[La^-]^b$, and training intensities through %HRmax (Garatachea et al., 2006; Psycharakis, 2011) enables evidence-based practice that would help practitioners to give informed training prescriptions.

When it comes to protocols or tests for VO_2 verification in swimmers with impairment, we recommend the incremental intermittent protocols with shorter duration in each swim series, e.g. N × 200m protocols and not N × 400m protocols. This is because the N × 200m incremental intermittent protocols are shorter in execution, with lower work rate and lower total respiratory volumes (VO2) compared to the N x 400m commonly performed by swimmers without physical impairment. Even in n x 200m protocols it is possible to obtain peak VO_2, which is similar to VO_{2max} for swimmers with physical impairments, by associating the swimming speed (Feitosa et al., 2020).

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