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RESEARCH ARTICLE

Kinematic, Coordinative and Efficiency Parameters of Physically Impaired Swimmers at Maximum Aerobic Power Speed

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Abstract:

Background:

In paralympic swimming, the biomechanical parameters related to performance are effectively determined according to the potentialities and peculiarities of each athlete. However, a clear integrated approach to these parameters for swimmers with physical disabilities at the speed of maximum oxygen uptake (vVO_{2max}) is still practically non-existent.

Objective:

The purpose of this study was twofold: (i) to assess kinematic, coordinative and efficiency parameters measured at vVO_{2max} in swimmers with physical impairments; and (ii) to correlate these biomechanical parameters with the time for a 200 m maximum test.

Methods:

Eleven swimmers with physical disabilities (seven males and four females) were assessed at vVO_{2max} with support from a three-dimensional kinematic method. The performance parameters analysed were: (i) kinematic - stroke rate (SR), stroke length (SL), average swimming speed (SS) and intra-cyclic velocity variation (IVV); (ii) coordinative - index of coordination (IdC) and adapted index of coordination (IdCadapt); and (iii) swimming efficiency - propelling efficiency (çp).

Results:

The overall results showed high dispersion and wide confidence intervals for the kinematic and coordinative variables. The mean and standard deviation of vVO_{2max} and VO_2 at the same intensity were 0.90 ± 0.13 m/s and 38.2 ± 8.3 ml/kg/min, respectively.

Conclusion:

Swimmers with less significant impact of physical disability on specific swimming tasks presented higher SL, SS and çp. The IVV was higher in swimmers with a greater impact of disability on conducting specific competitive swimming tasks. In general, the catch-up inter-arm coordination model is adopted.

Keywords: Adapted swimming, Disability, Paralympics, Oxygen uptake, Biomechanics, Coordination.

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1. INTRODUCTION

The different expressions of swimmers' movements can be assessed by kinematic, coordination and efficiency parameters [1 - 3]. Biomechanical studies seek to characterise the motor pattern and then improve efficiency in the execution of the movements [4]. In the case of swimmers with physical impairments, biomechanical analyses can contribute, for exam-ple, to understanding how different disabilities impact activity and sports performance [5, 6]. Considering the variability of physical disabilities and their effects on motor actions found during swimming, assessment of kinematic, coordinative and

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propelling efficiency could help clarify the possible impacts of physical disability on performance in adapted swimming.

Swimmers with physical impairments have different movement skills according to the severity of each disability [3, 7 - 9]. These swimmers are grouped in sports classes S1 to S10, from the greatest to the smallest impact of disabilities on carrying out certain specific sports tasks [10]. In addition to the sports classification of swimmers with disabilities, it is necessary to analyse each physical disability and its impact. For example, in case of swimmers with amputation of one of the upper limbs, there are disadvantages when compared to swimmers without a deficiency in the same limb, especially with regard to the hand and forearm, which represent the main propulsion surface [11 - 13]. Body balance is impaired by heavier and stiffer regions and, consequently, by deeper body submergence in water, *e.g.* swimmers with hemiplegia or paraplegia [14, 15], and the higher the drag value, the greater the disability [16].

Among the biomechanical parameters related to performance, (i) kinematics (such as stroke rate - SR, stroke length - SL, swimming speed - SS, and intra-cyclic velocity variation IVV, in its positive and negative accelerations); (ii) coordination (such as arm stroke phase duration and inter-arm coordination); and (iii) propelling efficiency (ηp) are extensively studied in conventional swimming [17 - 20]. However, among Paralympic swimmers, studies regarding these parameters are scarce [5, 21].

Propulsive efficiency is here understood as the mechanical power required to overcome drag in relation to the total mechanical power generated [22]. Since this ratio represents the theoretical efficiency of all fluid machines [23] and rowing animals [24], it is calculated in this study by the equation ηp = SS(3D)/3Du (Equation 1), where ηp is the propelling efficiency, SS(3D) is the three-dimensional (3D) speed of the centre of mass and 3Du is the 3D underwater speed of the hands [19].

Some studies have contributed to understanding biomechanical performance parameters in swimmers with physical disabilities [5, 21]. In this context, the studies have been dedicated to measurements of biomechanical parameters in competitive events or in short-distance protocols, both analysing mainly SS, SL and SR parameters, but just in two-dimensional (2D) kinematic analyses [7]. In addition, there are also studies dedicated to short-distance swimming assessments at short and long test paces in the analysis of kinematic and coordinative parameters in 2D [3, 25, 26]. Very rarely, studies are found with IVV analysis in a single case of a swimmer with amputation at elbow level (sport class S9) with 3D analysis [1] or even with a group of swimmers with the same deficiency at middle-distance pace, assessed by mechanical velocity meter [27]. Finally, just one study with longer courses analysed the parameters SS, SL, SR and IVV in 3D in intermittent incremental swimming protocols, but in sport classes S6, S8 and S9 [28].

Considering the importance of the maximum oxygen uptake swimming speed ($v\dot{V}O_{2max}$) to swimming performance [28, 29], little is known about the possible relationships between the physical functions of swimmers with disabilities and biomechanical performance parameters measured at $v\dot{V}O_{2max}$. Biomechanical parameters analysed at $v\dot{V}O_{2max}$ can be useful in training by coaches and swimmers by expressing a high level of motor control, energetic demand and recruitment of type II muscle fibres [30, 31]. This study adds information on a scenario of diverse deficiencies, some of which were not approached in a previous study [28], for example, sport classes S5, S7 and S10, with a larger set of kinematics, coordinative and swimming efficiency parameters at $v\dot{V}O_{2max}$. Regarding ηp, despite the existence of studies measuring propelling efficiency in non-disabled swimmers [32, 33], there are no studies, to our knowledge, on disabled swimmers (based on a preliminary search of the main databases, *e.g.* PubMed, ISI Web of Knowledge and SPORTDiscus). The results for these biomechanical parameters can provide information to improve performance in adapted swimming. In this sense, the purpose of this study was twofold: (i) to assess kinematic, coordinative and efficiency parameters measured at $v\dot{V}O_{2max}$ in swimmers with physical impairments; and (ii) to correlate these biomechanical parameters with the time for a 200 m maximum test.

2. MATERIALS AND METHODS

2.1. Participants

Eleven (seven males and four females) competitive swimmers (age 32.4 ± 12.4 years; height 1.73 ± 0.85 m; body mass 67.2 ± 9.9 kg; training background 6.4 ± 3.7 years) participated in this study. The study was approved by the local Ethics Committee and followed the guidelines of the Declaration of Helsinki. All the swimmers signed a written consent form in which the protocol was explained in detail.

Participants' sports classes [34], physical disabilities and number of participants were as follows: sport class S5 - hemiplegia, muscle stiffness and poor motor coordination (n = 1), spinal cord injury, T11-L1 (n = 1); sport class S7 - spinal cord injury, T11-T12 (n = 1); sport class S8 - spinal cord injury, L1-L2 (n = 1), one arm amputated near the shoulder (n = 1); sport class S9 - one forearm amputation (n = 1), one lower limb amputation near the hip (n = 3), congenital crooked foot sequelae and poor ankle mobility (n = 1); sport class S10 - amputation slightly below the knee (n = 1). All the participants had at least two years of experience in swimming competitions (regional, national or international).

2.2. Data Collection

Body mass (SECA® 813 digital scale, resolution of 0.1 kg, Hamburg, Germany) and height (SANNY stadiometer, Personal Caprice, resolution of 0.1 cm, São Paulo, Brazil) were measured [35]. Before the swimming tests, the participants received circular markers made by maceration of a dermatologically tested, solid and unctuous black paste applied with a sponge brush on the following anatomical points (except in the amputated joints): third digit, carpal region, olecranon, acromion, greater trochanter of the femur, lateral femoral condyle, lateral malleolus, ankles and hallux.

After a standardised warm-up of 600 m (swimming at low to moderate intensity according to individual experience), the participants performed an incremental intermittent test (N ×

200 m) with increments in speed of 0.05 m/s and 30 s rest intervals between each 200 m stage. The speed was controlled by a GBK2 pacer (Pacer2Swim, KulzerTec, Aveiro, Portugal) [36]. The front crawl technique was used by all the swimmers in a 25 m indoor swimming pool, underwater by using an Aquatrainer snorkel (Cosmed, Rome, Italy). Kinematic, coordinative and swimming efficiency data were obtained at $v\dot{V}O_{2max}$ (achieved in the fourth, fifth and sixth stages for different swimmers). The first step speed was previously determined in a 200 m front crawl all-out test performed in the same conditions as the incremental test.

Images for the acquisition of kinematic, coordinative and swimming efficiency parameters were recorded with the support of six fixed cameras (Sony Hdr cx260, 60 Hz, United States): four positioned below the surface line (0.5 m) inside watertight boxes (Sony SPK-HCH, United States) and two outside the water (1.52 m) (Fig. **1**). The images were synchronised using a device with manually activated light-emitting diodes, arranged above and below the water, in the centre of the pool and visible by all the cameras. The set-up and synchronisation were realised according to a previous study [37, 38].

One swimming stroke cycle comprises the entry and re-entry of the same hand into the water [17, 39]. A single stroke cycle was digitised for all swimmers at $v\dot{V}O_{2max}$. The term ‘stroke cycle’ was adapted for entry and re-entry of the distal part of the upper limb with amputation into the water. In this way, one stroke cycle was recorded by the cameras within a calibrated space (calibration structure with x = 4.5 m [horizontal axis]; y = 1 m [medial-lateral axis]; z = 1.5 m [vertical axis] dimensions). Regarding the reconstruction, the root mean square error for the x, y and z-axes was 1.92, 0.29 and 1.34 mm, respectively (ten real and ten control points for underwater and external cameras). The length of the upper limb was measured by the trigonometric relationship between the scapulohumeral joint and the third digit of the hand, including the mean relative angle between the forearm and the arm, for swimmers of equal age and gender [40].

2.3. Data Processing

After conducting the swimming tests, the images collected were divided and converted (AVCHD 1080p to AVI 1080 × 720p, uncompressed format) with Sony Vegas Pro 15 software (MAGIX GmbH & Co. KGaA, Germany). Subsequently, the images were digitised in the Ariel Performance Analysis System - APAS® (Ariel Dynamics Inc., California, USA) according to the anatomical markings, following a previously proposed anthropometric model [41]; transformed into numerical values (direct linear transformation) [42]; and filtered with a 4 Hz digital filter by residue analysis as suggested in the literature [43]. All the parameters were processed in 3D.

The kinematic parameters were (i) SR (Hz): the time obtained in seconds was transformed to Hz (inverse of the total cycle time) [44]; (ii) SL (m): the distance traveled by the body in a stroke cycle [11]; (iii) SS (m/s) - the mean velocity of the centre of mass in a stroke cycle obtained in 3D [38, 45]. The IVV was calculated by the coefficient of variation of the centre mass speed (dispersion of the instantaneous speed over the cycle by the average of the instantaneous cycle speed (m/s) in 3D) [38, 45].

The coordinative parameters in swimming were (i) the index of coordination (IdC) in swimmers without amputations or malformation in the upper limbs, and (ii) the adapted index of coordination (IdCadapt) for swimmers with an amputation slightly below the elbow (trans radio-ulnar). The IdC or IdCadapt was determined through the time interval between the propulsion actions of the two arms [46] or the delay between the propelling actions of the full arm and the arm with amputation [3]. The inter-arm coordination was categorised according to one of the three main models [3, 46]: (i) catch-up (time delay between the propulsion phases of the two arms; IdC or IdCadapt < 0); (ii) opposition (continuous series of propulsion actions, *i.e.* one arm starts the pulling phase when the other is finishing the pushing phase; IdC or IdCadapt = 0); and (iii) overlap (overlap, to a greater or lesser degree, of the propulsion phases; IdC or IdCadapt > 0).

The arm stroke was divided into four phases and their durations were identified: (i) entry and catch; (ii) pull; (iii) push; and (iv) recovery phase [3, 46]. The entry and catch phase was considered from the entry of the hand, or the distal part of the upper limb in the case of amputated swimmers, into the water until its maximum forward displacement. The pull phase was defined as the time between the end of the previous phase and the time when the hand or arm with amputation passes through the transverse plane to the shoulder joint. The push phase was defined starting from the end of the previous phase until the water hand comes out. The recovery phase was considered from the end of the previous phase until the hand re-entered the water. The sum of the pull and push phases was considered as the propulsive phase, and the sum of the recovery, entry and catch phases, as the non-propulsive phase. Each phase duration was expressed as a percentage of one complete stroke cycle duration.

The temporal characteristics of the stroke cycle were determined by the average duration of the complete stroke cycle (time), while the relative average duration of each phase was determined after digitising the first two consecutive strokes (one of the right arm and another of the left arm) [11]. From the moment the swimmers entered the previously calibrated space, for example, with the left arm, the IdC was defined as the time interval between the end of the left arm push phase and the beginning of the right arm pull phase (LT1), and the time delay between the end of the right arm push phase and the beginning of the left second arm pull phase (LT2) [11]. Independent of the hand that first entered the previously calibrated space, the mean delay between the propulsion phases of the two arms was presented as a percentage of the mean time of a complete stroke cycle (T) [11, 46], using Equation (2) for calculation of the IdC or IdCadapt:

$$\mathrm{IdC} = \frac{(\mathrm{LT1} + \mathrm{LT2})}{2} * \frac{100}{\mathrm{T}}$$

The propelling efficiency was calculated by the ratio of the 3D centre of mass body speed (SS) and the 3D hand speed (3Du) over a complete stroke cycle [22]. In the case of the swimmer with a complete upper-arm amputation, the ηp value was divided by two.

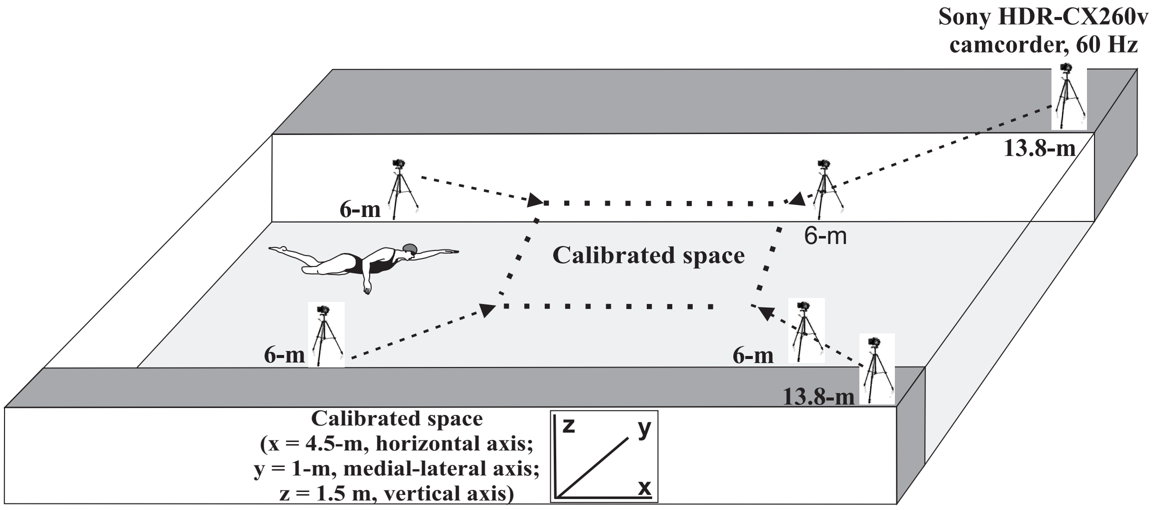

Fig. (1). Kinematic, coordinative and efficiency swimming data collection set-up over the N × 200 m protocol.

2.4. Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics software (version 25.0 for Windows; IBM Corp., Armonk, NY). Data distribution was checked with the Shapiro-Wilk test. The data presented normal distribution and were described as the mean ± standard deviation (SD) and 95% confidence interval of the mean (CI). An independent sample t-test was used to compare the mean of biomechanical variables among male and female swimmers. Statistical significance was set at $p < 0.05$. The figures were produced using GraphPad Prism (version 8.00 for Windows, GraphPad Software, La Jolla, California, USA). Pearson product-moment correlation tests were employed between pairs of kinematic variables (SS, SL, SR and IVV), coordinative variables (IdC and duration phases) and swimming efficiency (ηp), as well as all these biomechanical parameters in isolation with the result of the time-trial test (200 m). The correlation coefficients were considered [47]: < 0.1, trivial; 0.1-0.3, small; 0.3-0.5, moderate; 0.5-0.7, large; 0.7-0.9, very large; > 0.9, nearly perfect.

3. RESULTS

The results were expressed as the mean, SD and CI for the mean of swimmers with physical impairments for the kinematic (SR, SL, SS and IVV), coordinative (mean IdC and duration phases) and swim efficiency variables (ηp) measured at the speed of maximum oxygen uptake (Table **1**). The SS is equal to the $v\dot{V}O_{2max}$. The value of $\dot{V}O_2$ reached $v\dot{V}O_{2max}$ was 38.2 ± 8.3 ml/kg/min. The length of the upper limbs was slightly longer in male swimmers (upper limb length 0.55 ± 0.09 cm, CI 0.46-0.63) than in females (upper limb length 0.53 ± 0.04 cm, CI 0.47-0.59), but there was no statistical difference. The overall results showed high dispersion and wide confidence intervals for the kinematic and coordinative variables (Table **1**). The set of male and female swimmers adopted the catch-up model (IdC or IdCadapt < 0) (Table **1**). The IVV and ηp were similar between males and females (Table **1**).

When analysing the SR, SL and SS individually (Fig. **2-A** for males and Fig. **2-B** for females) and by gender, SR had greater variations in males (0.59 ± 0.10) than in females (0.67 ± 0.03). The SL and SS of male and female swimmers were higher in swimmers with a lower impact of physical disability except for the male swimmer of sport class S9 (SS of 0.86 m/s) and for the female swimmer of sport class S5 (SS of 0.76 m/s). The SL and SS were also higher in male swimmers (SL 1.48 ± 0.31 m; SS 0.93 ± 0.13 m/s) than in females (SL 1.20 ± 0.14 m; SS 0.85 ± 0.11 m/s).

The IVV was higher in male and female swimmers with lower SS, with the exception of the male swimmer of sport class S9 (SS 1.02 m/s; Fig. **2-C**) and the female swimmer of sport class S5 (SS 0.76 m/s; (Fig. **2-A**). There was a certain tendency of higher IVV for the most physically impaired swimmers (Fig. **2-C** for males and Fig. **2-D** for females). The exception to the sense of the highest to the lowest impact on carrying out specific swimming activities was included in sport class S9 for male swimmers and sport class S5 for female swimmers. In addition, the IVV was slightly higher in male swimmers (0.26 ± 0.10) than in females (0.22 ± 0.09) ($p > 0.05$).

The ηp seemed to be higher in the sport classes for less physically impaired athletes for male and female swimmers. Exceptions were the male swimmer of sports class S8 (ηp = 0.25, with a complete arm amputation,) who had a lower ηp than the male swimmer of sports class S7 (ηp = 0.31; spinal cord injury, T11-T12), and the female swimmer of sports class S5 (ηp = 0.29; hemiplegia, muscle stiffness and poor motor coordination) who had a higher ηp than the one in sports class S8 (ηp = 0.26; spinal cord injury, L1-L2). The ηp was similar in male (0.31 ± 0.07) and female (0.31 ± 0.05) swimmers (Fig. **2-C** and **D**).

The average percentage of inter-arm coordination (plotted on the left, **A**), arm phase duration percentage (centre, **B**) and the percentage of propulsive phases - pull and push (positioned on the right, **C**) for male and female swimmers are shown in Fig. **3**. The percentage of inter-arm coordination was higher in female swimmers (more positive) than in males ($t(8) = -2.41$; $p < 0.05$; Fig. **3-A**).

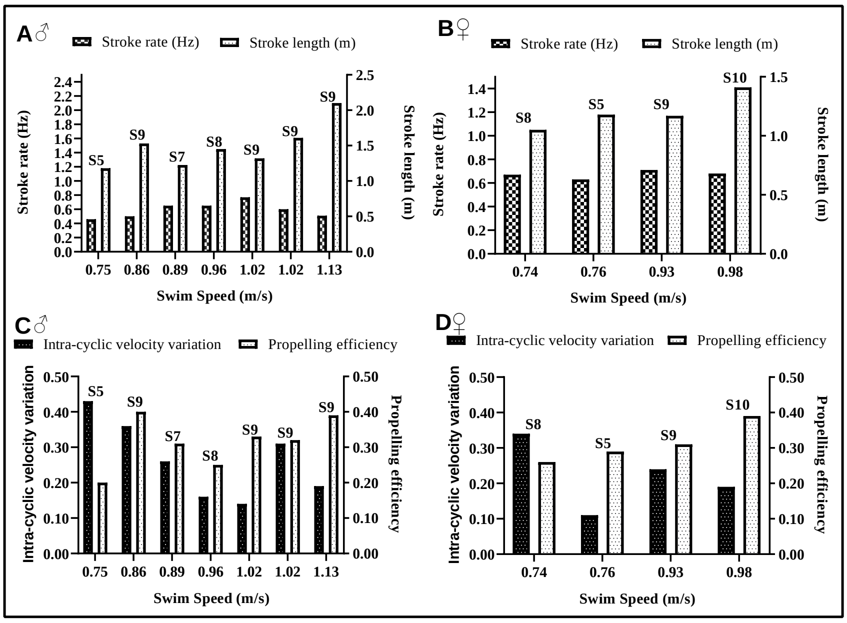

Fig. (2). Individual values for kinematic parameters (top image, **A**♂ for male, n = 7; **B**♀ for female, n = 4) and swim efficiency (bottom image, **C**♂ for male, n = 7; **D**♀ for female, n = 4) per swim speed and sport class of swimmers with physical impairments. For a description of the sport classes, see International Paralympic Committee. World Para Swimming: classification rules and regulations (2017).

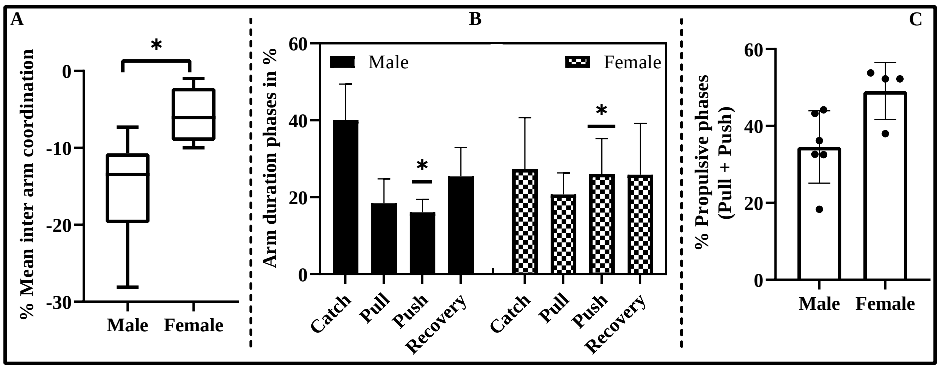

Fig. (3). Mean of inter-arm coordination (**A**), stroke phase (**B**) and propulsive phases (**C**) expressed as a percentage of total stroke time; * = $p < 0.05$, males (n = 6) and females (n = 4).

Table 1. Overall mean, standard deviation and mean confidence interval for kinematic, coordinative and propelling efficiency parameters at maximum oxygen uptake swimming speed.

Parameters	Overall Male and Female (mean ± SD)	95% Confidence Interval (Overall)
Kinematic, n = 11		
Stroke rate (Hz)	0.62 ± 0.09	0.54-0.68
Stroke length (m)	1.38 ± 0.29	1.15-1.59
Swim speed (m/s)	0.90 ± 0.13	0.80-0.99
IVV	0.24 ± 0.10	0.18-0.33
Inter-arm coordination, n = 10		
% IdC mean	−11.43 ± 7.48	−0.16 to −6.08
% Catch phase	34.97 ± 12.29	26.17-43.77
% Pull phase	19.34 ± 5.87	15.14-23.54
% Push phase	20.09 ± 7.79	14.51-25.66
% Recovery phase	25.59 ± 9.52	18.77-32.40
Swim efficiency, n = 11		
Propelling efficiency	0.31 ± 0.06	0.27-0.36

IdC = Index of coordination; IVV = Intra-cyclic velocity variation; SD = standard deviation.

Bivariate correlation analysis showed that swimmers with a higher SR also had the highest mean percentage of inter-arm coordination ($r = 0.65$; $p < 0.05$). This correlation coefficient was considered large (0.5-0.7). This correlation approximates the inter-arm coordination of the opposition model better for female swimmers (IdC −5.14 ± 7.05 in percentage) than for males (IdC −15.19 ± 7.07 in percentage).

The swimmers who had the longest duration of the catch phase (entry and catch) presented higher IVV ($r = 0.66$; $p < 0.05$). This correlation coefficient was considered large (0.5-0.7). On the other hand, the swimmers with a longer push phase had lower IVV ($r = -0.70$; $p < 0.05$). Regarding the percentage of arm phase duration, the push phase duration was higher in female swimmers than males ($t (8) = -2.49$; $p < 0.03$) (Fig. **3-B**). However, there was no difference ($p > 0.05$) in the percentage of propulsive phases (pull + push) between male and female swimmers (Fig. **3-c**).

The average time, SD and CI of a time-trial test (200 m, no block start, with the use of a snorkel) were 210.2 ± 48.0 s (CI 177.9-242.5). When investigating the possible bivariate correlations between a time-trial test (200 m) and all the parameters assessed (kinematic, coordinative and efficiency obtained at $v\dot{V}O_{2max}$), it was revealed that swimmers with higher SL, SS and ηp achieved the best performance in the 200 m maximum test, according to the respective correlation coefficient (respectively, $r = -0.71$; $p < 0.05$; $r = -0.87$; $p < 0.01$; and $r = -0.66$; $p < 0.05$). These correlation coefficients were considered very large (0.7-0.9) or large (0.5-0.7).

4. DISCUSSION

The purpose of this study was twofold: (i) to assess kinematic, coordinative and efficiency parameters measured at $v\dot{V}O_{2max}$ in swimmers with physical impairments; and (ii) to correlate these biomechanical parameters with time for a 200 m maximum test. Overall results of kinematic, coordinative and swimming efficiency parameters showed high dispersion in swimmers with physical impairments. In general, the inter-arm coordination model adopted was the catch-up. Analysis by gender showed higher SR results in female than male swimmers. On the other hand, the SL, SS, IdC or IdCadapt, and IVV variables were higher in male than female swimmers. The ηp was similar between both the genders. Individualised analyses showed that the SL and SS were high in developing specific swimming tasks. The IVV was higher in swimmers with a lower SS than in the faster ones. The IVV was higher in swimmers with a higher degree of impact of disability on developing specific competitive swimming tasks. The ηp was higher in the less physically impaired male and female swimmers enrolled in sports classes. Among the parameters investigated in the current $v\dot{V}O_{2max}$ study and the performance in the time-trial test (200 m), swimmers with higher SL, SS and ηp achieved a shorter time (best performance) in the 200 m.

Analysis of kinematic, coordinative and swim efficiency parameters in swimmers with physical disabilities is a notable challenge for researchers. Among some relevant aspects of research with Parasport participants is the variation of physical disabilities found [16]. The current study demonstrates high variability for the set of results related to male and female swimmers with physical disabilities (overall) for the time in the 200 m maximum test, as well as for the kinematic, coordinative (with adoption of the inter-arm coordination model in catch-up) and swim efficiency parameters (high IVV and ηp with less dispersion among the group of participants). Thus, each swimmer seeks motor solutions to compensate for physical losses and to enhance sports performance.

Gender analysis showed that male swimmers had higher SL, SS, inter-arm coordination in the catch-up model and IVV than female swimmers. Despite having found a similar study on the performance of swimmers with physical disabilities in incremental intermittent tests at maximum aerobic power [28], there was no distinction between genders. Some studies have demonstrated greater SS, SL and SR in male than female swimmers in 100 m freestyle events [7, 8, 48]. In short-distance events or protocols (50 and 100 m crawl), the shortest time was also achieved by male swimmers with physical disabilities compared to females [6].

The length of the upper limbs of the swimmers in the current study, measured at the beginning of the push phase, was slightly longer in male swimmers than in females, but there was no statistical difference. The upper limbs are the main body segments that greater influence SS and SL in the front crawl, although movements of the lower limbs and trunk in undulations and rotations can contribute to the propulsion force [11 - 13]. Regarding short events (100 m), there are studies that show a strong relationship between SL and the functional ability to increase SS in high-level swimmers with physical impairments [7, 8].

Other studies showed a greater SR influence on increasing SS than SL, especially for sport classes with a greater impact of physical disability on swimming (2 × 50 m maximum test with well-trained swimmers of sport classes S3-S10), but also for sport classes with a lower impact of physical disability on incremental intermittent swimming tests (N × 200 m with well-trained swimmers of sport classes S6, S8 and S9) [28]. In this sense, considering the sports classification of swimmers in our study, SL and SS were higher in swimmers with a lower impact of physical disability on developing specific swimming tasks than those with a higher impact. In incremental swimming tests with swimmers with a physical disability (sports classes S6, S8 and S9), higher SL (1.57 ± 0.29 in m) and SR (0.72 ± 0.06 in Hz) were presented than those found in the current study [49].

Swimmers with physical disabilities (sport classes S8-S9, mainly unilateral arm amputees) with a higher SR tend to swim with shorter gaps between the actions of the two arms (7 × 25 m in 3 min intervals of the two groups - the first group with slow speed to the maximum speed and the second group with the maximum speed to slow speed), adopting more positive inter-arm coordination models [3, 26]. In our study, swimmers with a higher SR presented a higher mean percentage of inter-arm coordination (more positive). Female swimmers were, on average, closer to the opposition model and had a longer duration of the push phase than male swimmers. However, the group of swimmers in this study seem to have preferred a longer SL as opposed to SR, having adopted the catch-up model at $v\dot{V}O_{2max}$. In another study, swimmers with physical impairment (sport class S5-S10, 100 m competitive event) also adopted the catch-up model in a slightly higher percentage (IdC = −0.17) and had longer propulsive phases (pull = 28.29% and push = 25.60%) [25] than those found in the current study. The swimmers who had a longer catch phase presented a higher IVV in our study. While the catch phase is not propulsive, swimmers tended to reduce their SS [3, 26]. On the other hand, the pull phase (end of the catch phase until the hand is below the shoulder) is propulsive, and the swimmers with a longer pull phase had a lower IVV ($r = 0.66$; $p < 0.05$).

In relation to swimming efficiency, the IVV was higher in swimmers with a lower SS than in the faster ones. The most striking exception was the third male swimmer of sport class S9 (SS 1.02 m/s) in the order of the lowest to the highest speed. In case of the female swimmer of class S5 (SS 0.76 m/s), there was also a small difference in SS between her and the female swimmer of sport class S8 (SS 0.74 m/s). The IVV was higher in swimmers who were more physically impaired for performing competitive swimming tasks than in swimmers who were less physically impaired. The apparent divergence to this argument occurs within the sports class S9 for male swimmers and S5 for the female swimmer. Within the same sports class, there are different deficiencies that impact how specific sport swimming tasks are performed [50]. These different deficiencies limit or impact accelerations and decelerations within the swimming cycle [1, 27].

In order to reduce the apparent divergence, we point out, for example, that in this study, the swimmer of sport class S9 had the largest IVV and he had amputation in part of the upper limb (amputation at the elbow level, n = 1; IVV 0.36 in %), followed by swimmers with an amputation in the lower limb (the upper knee, n = 2; IVV 0.25 ± 0.08 in %); the next was the swimmer with a congenital malformation in both feet (IVV 0.14 in %). A study with swimmers of sport class S9 (amputation at elbow level, n = 8, two males and six females) developed at mid-distance pace (without legs) showed an IVV similar (IVV 35 ± 5 in %) [27] to that found for the swimmer of sports class S9 with elbow-level amputation in the current study (IVV 36 in %), and was higher than the IVV of our swimmers in sports class S9 (n = 5, four males and one female, IVV 0.24 ± 0.08 in %).

In case of the female swimmer in sports class S5 (with hemiplegia), the lowest IVV found in relation to the swimmer in sports class S8 (mild paraplegia) was probably due to the movements of the arm affected by hemiplegia, even with poor motor control compared to the absence of almost complete movements of the lower limbs (sport class S8). Swimmers with tetraplegia, high-level paraplegia and those with spasticity have more difficulties than swimmers with low-level paraplegia and with amputations in maintaining their body in a more horizontal (streamlined) position in water [51].

The ηp seems to be higher in the sports classes for less physically impaired male and female swimmers. In our study, we mentioned as a possible exception the swimmer of sports class S8 ($\eta p = 0.25$) who had a lower ηp than the swimmer of sport class S7 ($\eta p = 0.31$). However, when analysing the disability and not the sport classification, the sport class S8 swimmer had a complete arm amputation. This complete arm amputation produces a direct impact on the ηp compared to the disability of the swimmer of sport class S7 who had both arms without disability (spinal cord injury, T11-T12). In turn, the female swimmer of sports class S5 had slightly more severe hemiplegia ($\eta p = 0.29$) than the female swimmer of sports class S8 with spinal cord injury, L1-L2 ($\eta p = 0.26$). No studies on ηp were found on swimmers with physical disabilities. The ηp and SS (ηp 0.31 ± 0.06 and SS 0.90 ± 0.13 in m/s at $v\dot{V}O_{2max}$) of swimmers with a physical disability were lower than ηp and SS (ηp 0.36 ± 0.03 and SS 1.46 ± 0.06 in m/s as $v\dot{V}O_{2max}$) of non-disabled swimmers (high-level male swimmers) in protocols similar to those of the present study.

Particularly in swimmers with physical disabilities, the best performance is expected for those with less impact of the disability on the ability to perform specific competitive swimming tasks [50]. When investigating possible correlations between the time-trial test (200 m) and the parameters measured in the incremental intermittent test at $v\dot{V}O_{2max}$ (kinematic, coordinative and swim efficiency), it was revealed that swimmers with higher SS, SL and ηp achieved shorter times for the 200 m maximum test. These results seem to be relevant in the training of swimmers with disabilities at average distances for their similarity with those obtained in the incremental test at $v\dot{V}O_{2max}$.

The current study presents as limitations the sample size and the great variation in physical disabilities (the variability possibly interacts with the biomechanical variables). These limitations make both the extrapolation of results to all populations and the separation of the effect of experience level (regional and international) and the effect of impairment difficult, as both affect the swimming performance. In this way, this analysis requires careful case-by-case investigation.

CONCLUSION

Overall, there is a high variability in kinematic, coordinative and swimming efficiency parameters in swimmers with physical disabilities. The inter-arm coordination model adopted was captured for all swimmers. Swimmers with less impact of physical disability on developing specific swimming tasks presented higher SL, SS and ηp. The IVV was higher in swimmers with a greater impact of disability on performing specific competitive swimming tasks. Swimmers with higher SL, SS and ηp measured at $v\dot{V}O_{2max}$ achieved shorter times in the time-trial test (200 m). The data supporting the findings of the article is available in the attached file "Individual Data".

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The local Ethics Institutional Review Board approved the procedures (2.274.037).

HUMAN AND ANIMAL RIGHTS

No animals were used in this research. All human research procedures followed were in accordance with the ethical standards of the committee responsible for human experimentation (institutional and national), and with the Helsinki Declaration of 1975, as revised in 2013.

CONSENT FOR PUBLICATION

Written informed consent was obtained from all individual participants.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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