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Kinematic variables of disabled swimmers and their correlation with the IPC classification

Introduction

Improvement in swimming performance depends on the applied technique by swimmers (Nikodelis et al., 2005). Although kinematics evaluation of swimming has described aspects of a set of performance variables (Figueiredo et al., 2013; McCabe et al., 2015; Puel et al., 2012), only a few studies have evaluated such variables among disabled swimmers. Assessing such variables is essential for a better understanding of the factors associated with Paralympic performance (Dos Santos et al., 2019; Feitosa, Correia, Barbosa, & de Souza Castro, 2019). Physical and motor constraints in disabled swimmers must be analyzed with caution since they may differ concerning the non-disabled swimmers. These constraints may impose specific challenges (Fulton et al., 2010), as disabled swimmers may have more difficulties sustaining a streamlined position to minimize passive drag resistance forces depending on the disability (Payton et al., 2020) or its severity (Oh et al., 2013). Thus, coaches and researchers of this area should be cautious about the assumptions made through their findings (Satkunskiene et al., 2005; Taylor et al., 2016).

Disabled swimmers present different physical impairment levels, which are applied to classify participants (Hogarth et al., 2018). In general, swimming classification is based on strength, coordination, range of motion and/or segment length (Burkett et al., 2010; Pelayo et al., 1999) and functionality (Puce et al., 2019; Tweedy & Vanlandewijck, 2011). The physically impaired classes range between 1 and 10 (excluding vision and intellectual impairments). Low values represent greater impairment, and high values indicate lower impairment (Fulton et al., 2009; Oh et al., 2013; Pelayo et al., 1999). Thus, comparable performances can be obtained by swimmers with different impairments (Satkunskiene et al., 2005), as the classification is designed to gather evenly matched classes. For example, swimmers with amputation, injury, and cerebral palsy may be grouped into the same class (Malone et al., 2001; Pelayo et al., 1999; Wu & Williams, 1999). However, there is limited information based on objective parameters to support the current classification system

(Barbosa et al., 2020; Burkett et al., 2018; Hogarth et al., 2018). Indeed, discrepancies in the functional classification of disabled swimmers have led to controversies (Gehlsen & Karpuk, 1992; Wu & Williams, 1999).

Burkett et al. (2018) indicated that the classification system delineates performances between some classes but is inconsistent and may disadvantage some swimmers. However, Wu and Williams (1999) have affirmed efficiency in the classification system since swimming speed was positively correlated with the Paralympic Games of Atlanta classes. Besides, the authors did not find a dominant impairment in participation opportunity, winning medals, and advancing to the finals. Fulton and associates also reported a positive association between functional class and the mean time to race completion (Fulton et al., 2009). Finally, Dingley and colleagues found a higher start velocity among less severe functional classes when compared to medium and high severity classes (Dingley et al., 2014). The classification protocol has undergone multiple revisions over time and indicates the importance of new investigations to clarify and contribute to further improvements in the classification system (Puce et al., 2019). Thus, different perspectives of physiological and biomechanical para-swimming studies are necessary (Oh et al., 2013; Wu & Williams, 1999).

The present study aimed to describe the variables of disabled swimmers' performance at 50m distance and correlate a set of biomechanical parameters of the swim with the functional classification proposed by the International Paralympic Committee. It was hypothesized that the swimming velocity, stroke length, and percentage of time spent in the underwater phase are positively correlated with the IPC classification, while stroke frequency is not associated.

Methods

Participants

Twenty-one physical impaired swimmers (19.2 ± 2.82 years, males: 1.70 ± 0.06 m, 61.49 ± 10.68 kg, and females: 1.61 ± 0.10 m, 56.60 ± 10.31 kg to stature and weight respectively) participated in this study. The inclusion included: (i) age equal or greater than 15 years, (ii) at least three-year of competitive experience, (iii) minimum regular training session five times weekly. Also, the disabled swimmers should be previously classified according to the International Paralympic Committee of classes between S5 and S10 (IPC, 2015). Impairments included amputation at the elbow level, cerebral palsy, myelomeningocele, brachial plexus paralysis, arthrogryposis, double leg amputation at knee level, congenital malformation, dwarfism, and spina bifida.

The group was composed of 11 Brazilian and 10 British disabled swimmers. Before any procedures, participants and/or parents or guardians signed an approved informed consent document to participate in the study. The institutional Ethics Committee approved all data collection procedures.

Data collection

Data collection was recorded by four underwater cameras, synchronized by a light pulse positioned in the visual field of all cameras. The underwater cameras used with Brazilian swimmers were the GoPro Hero 4 with frequency acquisition at 60 Hz, while British swimmers were filmed by Mako G-223B from Allied Visions Technology placed in underwater housings Autovimation Nautilus (IP 68 rated) with a frequency of 50 Hz. The cameras were fixedly positioned diagonally on the swimmer sides with approximate angles of 90° between each other. The camera field of view was set in 127º, and possible distortion effect was removed by applying “lens adjustment” setting in the GoPro Studio software. Each camera focused on a volume previously calibrated in the pool with the measures of 3.5 m length (x), 1.0 m wide (y), and 1.5 m deep (z), with 54 underwater control points. The markers were positioned in the dominant side of the evaluated anatomical points: distal phalanx of the 3rd metacarpal (or segment extremity for arm amputee swimmers at the elbow level) and greater trochanter of the femur. The markers used in the British swimmers were drawings with a waterproof marker pen (diameter ~25 mm), while Brazilian swimmers used a suit made especially for this study with LED light markers. Further details regarding marker types can be found elsewhere (Dos Santos et al., 2017; Santos et al., 2017).

Experimental procedures

Swimmers were invited to participate in a single experiment session held in a 25 m swimming pool (~ 28° C). Anthropometric measurements (body mass, stature, and arm span) were taken before testing. After 600 m of uninstructed warm-up, swimmers were instructed to perform 50 m maximum front crawl swimming. Swimmers were asked not to breathe when they entered the calibrated area to diminish the possible effects of the breathing. The start was performed from inside the pool, and the participants received verbal encouragement during the test.

The markers were digitized in specific kinematic analysis software (SIMI Reality Motion Systems), and the repeated digitizing process of the measurement showed highly reproducible and replicable (ICC ranged from 0.99 to 1.0) and small accuracy error (<0.01 m). More details of reliability data have been previously described (Santos et al., 2017). The two-dimensional coordinates were filtered at 7 Hz using a low-pass Butterworth filter (2^{nd} order). They were then converted into three-dimensional coordinates using a direct linear transformation (DLT) algorithm (Silvatti et al., 2013).

Data analysis

A complete stroke cycle was analyzed, defined by the entry of one upper body segment into the water until the subsequent entrance of the same segment. The cycle was divided into four phases adapted from Payton et al. (1999).

Glide + Downsweep (D_s): from the entry hand to the most lateral position of the hand (or segment extremity for arm amputee swimmers).

Insweep (I_s): from the end of the downsweep to the most medial position of the hand.

Upsweep (Us): from the end of the insweep to hand exit.

Recovery: from the end of the upsweep to next hand entry.

The first three phases correspond to the underwater phases of the stroke. The following parameters, according to Dos Santos et al. (2019) were analyzed:

Swimming velocity: the product between the stroke rate and stroke length.

Stroke rate (SR): calculated by extrapolating the number of cycles per minute by the time spent to perform a single stroke.

Stroke length (SL): distance traveled by the body during a stroke cycle.

Intracyclic velocity variation (IVV): estimated by the coefficient of variation of the rate of hip progression (ratio of the standard deviation of the mean velocity of the hip displacement on the x-axis, by the mean hip velocity on the same axis during a stroke cycle)

Stroke width: displacement of the y axis by the difference between the most lateral and medial position.

Stroke depth: displacement of the z axis between the entry of the hand in the water to the deepest point.

Underwater stroke amplitude: displacement on the x axis by the difference between entry and exit of the hand in the underwater phase.

Percentage of time in the submerged phase (T_{sub}): percentage time spent between hand input and output in the water in relation to the total stroke cycle time.

Coordination index (IdC): adapted from Chollet et al.(Chollet et al., 2000), considering the percentage of strokes opposition ($IdC = 0$), time lapse ($IdC < 0$) or overlap of arms ($IdC > 0$) in the propulsive phase (insweep + upsweep).

*Mean velocity of the hand in the underwater ph*ase: the ratio between the trajectory resulting from the underwater phase and the time spent to complete this phase.

Mean velocity of the hand in each submerged stroke phase: the ratio between the trajectory in each underwater phase (downsweep, insweep, and up sweep) and the time spent to complete each phase.

Statistical analysis

Shapiro-Wilk and Levene tests were applied to verify the normality and homogeneity of the data. Descriptive statistics (mean and standard deviation) and Kendall rank correlation (due to the nonparametric characteristic of the data) between functional classification and stroke parameters (velocity, SL, SR, and T_{sub}) were determined. Statistical analysis was performed using specific software (Statistica, version 7, Statsoft Inc.) with significance at $p < 0.05$.

Results

The swimmers' velocity was 1.17 ± 0.23 $m.s^{-1}$, SL 1.47 ± 0.25 m, SR 47.95 ± 5.00 cycles. min^{-1} and T_{sub} 69.59 ± 4.79%. The correlations between these swim variables and the IPC functional classification are presented in Figure 1. The swimming velocity and SL showed a moderate positive correlation with the functional classification ($p < 0.05$). The SR did not show correlation with the IPC classification, and the T_{sub} showed a weak correlation.

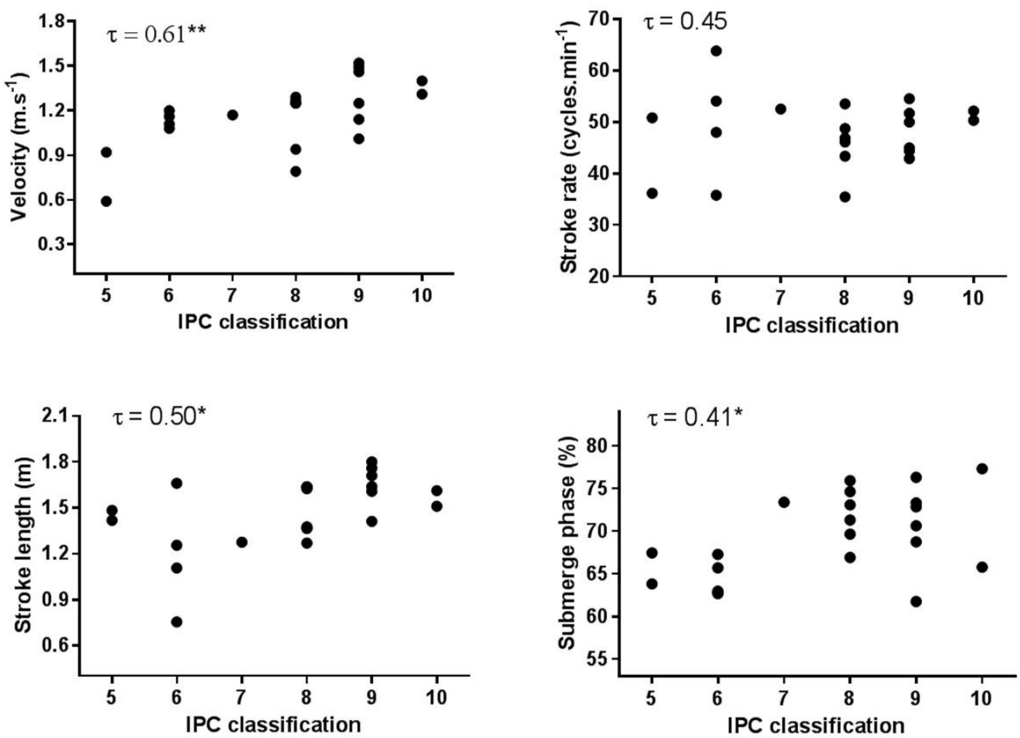

Figure 1 Swimming variables x IPC classification

The aspects of the underwater stroke phase showed considerable variability among swimmers with a width range between 0.16 and 0.42 m and depth between 0.51 and 0.85 m. The amplitude of the underwater stroke ranged between 0.41 and 0.75 m. Half of the swimmers showed time lag between the propulsive phases of the arm stroke (IdC <0), 45% overlapping stroke (IdC >0), and only 1participant arm opposition coordinator (IdC =0).

Table 1 - Individual values, mean, standard deviation, maximum and minimum values of disabled swimmers stroke variables.

Participants	IPC Classification	Stroke amplitude	Stroke width	Stroke depth	Coordination index
P1	S5	0.58	0.32	0.70	-10
P2	S5	0.55	0.33	0.64	6
P3	S6	0.55	0.23	0.72	-7
P4	S6	0.50	0.16	0.60	0
P5	S6	0.55	0.30	0.63	-1
P6	S6	0.57	0.18	0.51	4
P7	S7	0.69	0.42	0.85	-1
P8	S7	0.41	0.24	0.54	-
P9	S8	0.67	0.40	0.68	6
P10	S8	0.59	0.32	0.68	-7
P11	S8	0.75	0.36	0.63	3
P12	S8	0.63	0.31	0.82	-5
P13	S8	0.50	0.41	0.63	-7
P14	S8	0.60	0.32	0.75	8
P15	S9	0.31	0.24	0.51	10
P16	S9	0.72	0.20	0.82	-5
P17	S9	0.44	0.33	0.85	-8
P18	S9	0.68	0.24	0.72	8
P19	S9	0.50	0.32	0.64	9
P20	S10	0.65	0.16	0.62	-7
P21	S10	0.65	0.30	0.64	7
Mean		**0.58**	**0.29**	**0.68**	**0.16**
SD		**0.11**	**0.08**	**0.10**	**6.94**
Maximum		**0.75**	**0.42**	**0.85**	**10**
Minimum		**0.31**	**0.16**	**0.51**	**-10**

The swimmers' hand velocity during downsweep was 1.80 ± 0.29 ms-1, while insweep 2.04 ± 0.59 $m.s^{-1}$ and upsweep 2.28 ± 0.36 $m.s^{-1}$. The average hand velocity in the whole submerged phase was 2.10 ± 0.24 $m.s^{-1}$. Finally, the IVV was 0.24 ± 0.09. Functional classification did not significantly correlate with hand velocity at any phase, IdC or IVV (τ between -0.11 and 0.36; $p > 0.05$).

Discussion

This study described three-dimensional kinematics variables of disabled swimmers and correlated them with IPC swimming classification. The SL and SR observed in the present study are in line with reported by Pelayo et al. (1999) when considering the same classes - S5 to S10 (mean SL = 1.44 m, SR = 50.0 $cycles.min^{-1}$, swim velocity = 1.19 ms^{-1}).

The great variability observed among the swimmers may reflect the individual characteristics of the impairment (Osborough et al., 2010). Despite the variability between classes, it was possible to observe a moderate relationship between three evaluated variables with the classification (velocity, SL and T_{sub}). These results support the current classification, with a higher swimming velocity, SL and T_{sub}, there is a higher classification stratum, i.e. the lower the severity of the disability. Daly et al. (2003) also found that SL decreases with functional class, while SR did not significantly change. Feitosa and colleagues reported that swimming velocity and stroke length increase with less impact of disability, while stroke rate remains more stable between functional classes (Feitosa, Correia, Barbosa, & Castro, 2019).

The way that classification is determined may explain the results since it considers several aspects: range of motion, strength, and coordination. These elements are related to the ability of the swimmer to extend the arm (or the correspondent segment) forward during the entrance and the finalization of the underwater phase with the complete extension of the arm or segment. The amplitude of the stroke impacts the SL and consequently the velocity of swimming. Moreover, the longer the underwater phase, the greater the ability to apply force and generate momentum. For instance, Dingley et al. (2014) observed a lower percentage of time spent in the underwater phase among lower class swimmers.

The stroke rate was not correlated with the classification. Maybe using different strategies to obtain maximum velocity has been used as a compensatory mechanism for physical disability. Satkunskiene et al. (2005) suggested that SL is better than SR to predict velocity for all functional classes of impaired swimmers. In fact, in the present study, SL was moderately correlated with the classification system ($r = 0.55$), while SR was not correlated.

The mean stroke width of the disabled swimmers was lower than able-body swimmers (McCabe et al., 2011; McCabe & Sanders, 2012). The anthropometric profile can explain these differences (Dingley et al., 2014), by the limitation of motion range that is usually present due to the impairment, since restrictions in flexibility can impair performance even in non-disabled swimmers (Sanders et al., 2011). The depth of the stroke was close to those exhibited by non-disabled high-level swimmers (McCabe et al., 2011; McCabe & Sanders, 2012). Thus, stroke depth does not seem to be able to differentiate disabled swimmers from able-bodied ones.

The coordination index did not correlate with the IPC classification and indicated, on average, an overlap mode. It must be interpreted with caution since the data showed high dispersion, and individual analysis revealed the adoption of the three coordination models. Feitosa and colleagues also reported high dispersion to IdC results but in a catch-up model (Feitosa, Correia, Barbosa, & de Souza Castro, 2019). The longest swimming distance used, and consequently, lower SR results (i.e., ~37cycles.min^{-1}), may explain the difference. Indeed, Satkunskiene et al. (2005) observed for locomotor disability swimmers, that greater amounts of more skilled ones adopted superposition coordination models and showed higher SR when compared to less skilled swimmers.

Hand velocity displacement showed a successive increase during the submerged phases, which also occurred in non-disabled swimmers (Maglischo, 2003). However, the velocity of the phases was not correlated with the functional classification. Although average hand velocity in the submerged phase was close to that reported previously for non-disabled swimmers (Gourgoulis et al., 2010), the swimming velocity was considerably lower. It seems that the hand velocity of impaired swimmers was not being optimized for the body's displacement. It may be likely that the disabled swimmers are applying this hand velocity with less technical quality. In fact, the contribution of the hands to the swimming efficiency depends on the direction, trajectory, and angle of propulsive force application (Maglischo, 2003; Schleihauf et al., 1988).

The efficiency of the stroke results from the ratio between the velocity of swimming and the mean of hands velocity (Alexander, 1983). Since disabled swimmers presented lower body velocity and similar hand velocity to non-disabled swimmers, it is assumed that they exhibited lower stroke efficiency. The higher passive drag presented by the severity of the impairment, due to their body shape and body position in the water that influence the swimmers to maintain the most streamlined position (Oh et al., 2013), may contribute to the lower stroke efficiency as well as their reduced capacity to generate propulsive force (Lee et al., 2014).

The intracycle velocity variation among disabled swimmers was higher than those found for non-disabled swimmers (Figueiredo et al., 2016), which may influence swimming efficiency. Considerable intracycle velocity variation exposes swimmers to high resistive forces due to the alteration of impulses that affect the energy cost of swimming (Barbosa et al., 2008). Further research on the intracycle velocity variation of disabled swimmers needs to be conducted to compare data. For instance, the IVV results are higher than those reported by Marques-Aleixo et al. (2013) to swimmers with Down Syndrome in breathless condition. The slowest swimming speed showed by the cognitively impaired swimmers may have helped them generate less turbulence and apply propulsive force with greater continuity. Indeed, Figueiredo et al. (2014) found a positive correlation between IVV and speed to an arm-amputee swimmer.

Conclusion

This article provides an overview for coaches regarding kinematics of disabled swimmers and the relation of these variables with the IPC classification. The swimmers of lower functional classification levels (i.e., S1-S4) were not included, which comprises limitations of the study. Furthermore, the only front crawl was analyzed, while classifiers also consider other swimming stroke, and performance in fatigue conditions was not evaluated, which may not reflect the whole race. Velocity and stroke length was moderately correlated with the functional classification, while the percentage of time spent in the underwater phase showed a weak correlation. On the other hand, the velocity of the hand displacement from disabled swimmers was not correlated with the functional classification and can be a critical point for high-level performance. The optimization in the direction and velocity of hand displacement seems to be necessary.

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