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Dos Santos, Karini Borges, Bento, Paulo Cesar Barauce, Payton, Carl  and Rodacki, André Luiz Felix (2021) Kinematic Variables of Disabled Swimmers and Their Correlation With the International Paralympic Committee Classification. *Motor Control*, 25 (4). pp. 575-586. ISSN 1087-1640

DOI: <https://doi.org/10.1123/mc.2021-0019>

Publisher: Human Kinetics

Version: Accepted Version

Downloaded from: <https://e-space.mmu.ac.uk/628374/>

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

2 **Introduction**

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

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

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

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

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

47 **Methods**

48 **Participants**

49 Twenty-one physical impaired swimmers (19.2 ± 2.82 years, males: 1.70 ± 0.06 m, $61.49 \pm$
50 10.68 kg, and females: 1.61 ± 0.10 m, 56.60 ± 10.31 kg to stature and weight respectively)

51 participated in this study. The inclusion included: (i) age equal or greater than 15 years, (ii) at least
52 three-year of competitive experience, (iii) minimum regular training session five times weekly.
53 Also, the disabled swimmers should be previously classified according to the International
54 Paralympic Committee of classes between S5 and S10 (IPC, 2015). Impairments included
55 amputation at the elbow level, cerebral palsy, myelomeningocele, brachial plexus paralysis,
56 arthrogryposis, double leg amputation at knee level, congenital malformation, dwarfism, and spina
57 bifida.

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

62 **Data collection**

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

76 for this study with LED light markers. Further details regarding marker types can be found
77 elsewhere (Dos Santos et al., 2017; Santos et al., 2017).

78 **Experimental procedures**

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

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

92 **Data analysis**

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

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

98 *InswEEP* (I_s): from the end of the downsweep to the most medial position of the hand.

99 *Upsweep* (U_s): from the end of the insweep to hand exit.

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

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

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

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

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

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

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

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

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

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

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

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

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

125 *Statistical analysis*

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

131

Results

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

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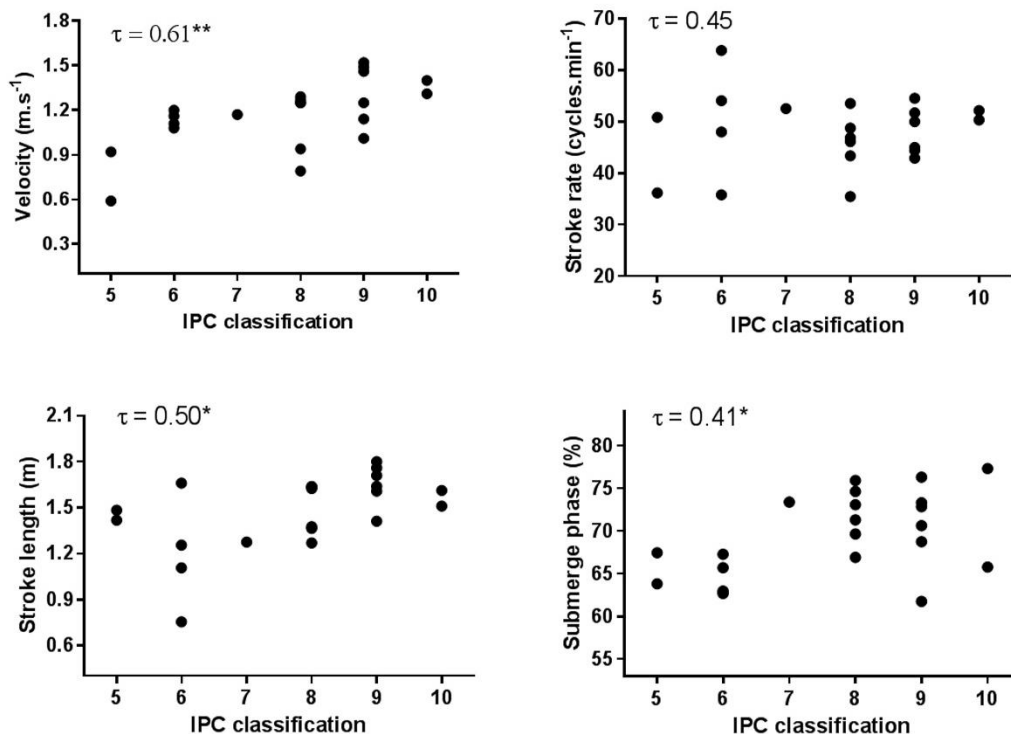


Figure 1 Swimming variables x IPC classification

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

155 **Table 1 - Individual values, mean, standard deviation, maximum and minimum values of**
 156 **disabled swimmers stroke variables.**
 157

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

158 The swimmers' hand velocity during downsweep was $1.80 \pm 0.29 \text{ ms}^{-1}$, while insweep 2.04
159 $\pm 0.59 \text{ m}\cdot\text{s}^{-1}$ and upsweep $2.28 \pm 0.36 \text{ m}\cdot\text{s}^{-1}$. The average hand velocity in the whole submerged
160 phase was $2.10 \pm 0.24 \text{ m}\cdot\text{s}^{-1}$. Finally, the IVV was 0.24 ± 0.09 . Functional classification did not
161 significantly correlate with hand velocity at any phase, IdC or IVV (τ between -0.11 and 0.36 ; $p >$
162 0.05).

163

Discussion

164 This study described three-dimensional kinematics variables of disabled swimmers and
165 correlated them with IPC swimming classification. The SL and SR observed in the present study are
166 in line with reported by Pelayo et al. (1999) when considering the same classes - S5 to S10 (mean
167 $SL = 1.44 \text{ m}$, $SR = 50.0 \text{ cycles}\cdot\text{min}^{-1}$, swim velocity = 1.19 ms^{-1}).

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

177 The way that classification is determined may explain the results since it considers several
178 aspects: range of motion, strength, and coordination. These elements are related to the ability of the
179 swimmer to extend the arm (or the correspondent segment) forward during the entrance and the
180 finalization of the underwater phase with the complete extension of the arm or segment. The
181 amplitude of the stroke impacts the SL and consequently the velocity of swimming. Moreover, the
182 longer the underwater phase, the greater the ability to apply force and generate momentum. For

183 instance, Dingley et al. (2014) observed a lower percentage of time spent in the underwater phase
184 among lower class swimmers.

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

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

197 The coordination index did not correlate with the IPC classification and indicated, on average,
198 an overlap mode. It must be interpreted with caution since the data showed high dispersion, and
199 individual analysis revealed the adoption of the three coordination models. Feitosa and colleagues
200 also reported high dispersion to IdC results but in a catch-up model (Feitosa, Correia, Barbosa, & de
201 Souza Castro, 2019). The longest swimming distance used, and consequently, lower SR results (i.e.,
202 $\sim 37 \text{cycles} \cdot \text{min}^{-1}$), may explain the difference. Indeed, Satkunskiene et al. (2005) observed for
203 locomotor disability swimmers, that greater amounts of more skilled ones adopted superposition
204 coordination models and showed higher SR when compared to less skilled swimmers.

205 Hand velocity displacement showed a successive increase during the submerged phases,
206 which also occurred in non-disabled swimmers (Maglischo, 2003). However, the velocity of the
207 phases was not correlated with the functional classification. Although average hand velocity in the

208 submerged phase was close to that reported previously for non-disabled swimmers (Gourgoulis et
209 al., 2010), the swimming velocity was considerably lower. It seems that the hand velocity of
210 impaired swimmers was not being optimized for the body's displacement. It may be likely that the
211 disabled swimmers are applying this hand velocity with less technical quality. In fact, the
212 contribution of the hands to the swimming efficiency depends on the direction, trajectory, and angle
213 of propulsive force application (Maglischo, 2003; Schleihau et al., 1988).

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

221 The intracycle velocity variation among disabled swimmers was higher than those found for
222 non-disabled swimmers (Figueiredo et al., 2016), which may influence swimming efficiency.
223 Considerable intracycle velocity variation exposes swimmers to high resistive forces due to the
224 alteration of impulses that affect the energy cost of swimming (Barbosa et al., 2008). Further
225 research on the intracycle velocity variation of disabled swimmers needs to be conducted to
226 compare data. For instance, the IVV results are higher than those reported by Marques-Aleixo et al.
227 (2013) to swimmers with Down Syndrome in breathless condition. The slowest swimming speed
228 showed by the cognitively impaired swimmers may have helped them generate less turbulence and
229 apply propulsive force with greater continuity. Indeed, Figueiredo et al. (2014) found a positive
230 correlation between IVV and speed to an arm-amputee swimmer.

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Conclusion

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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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