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Research article

Effects of distance specialization on the backstroke swimming kinematics

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Abstract
The purpose of the present study was to investigate different biomechanical variables of backstroke technique in swimmers specialized in different distance events, in order to investigate the capacity to modify the timing of the arm stroke when changing the swimming velocity from sub-maximal to maximal. Two 25-m backstroke trials respectively at 70% of maximum velocity (V70) and at 100% of maximum velocity (Vmax) were performed by 9 200-m distance swimmers and 9 50-m distance swimmers. Swimming velocity, stroke length, stroke rate, duration of different phases of the arm stroke and selected kinematic variables were assessed in both cases. In the 50-m distance swimmers, the duration of the propulsive phase at Vmax, expressed as a percentage of the duration of the total underwater arm stroke, increased significantly ($p = 0.001$) with increasing swimming velocity. Specifically, both the pull and push phases were fundamental in the increase of duration of the propulsive phase. When compared to 200-m specialists, 50-m distance swimmers seem to be more able to modify their arm stroke phases duration when increasing the swimming velocity in backstroke.

Key words: Arm motion, stroke phases, stroke rate, stroke length, technical analysis.

Introduction

Backstroke swimming is a cyclic movement. Thus, the mean velocity, representing the best measure of swimming performance (Craig and Pendergast,1979), is given by the product between stroke rate (SR) and stroke length (SL) (Barbosa et al., 2008a; Craig and Pendergast, 1979). How the athletes modify these parameters to increase velocity is of great interest. A reduction of SL is associated to a reduction of the swimming velocity, in all the strokes (Hay and Guimarães, 1983). In such a case, the only solution for a swimmer to maintain the same velocity is to increase the SR (Craig and Pendergast, 1979). When comparing different swim paces in backstroke, from 200 to 50 m, the velocity and the SR increase, while the SL decreases (Chollet et al, 2008).

The period of the backstroke swimming can be subdivided into two phases, namely an aerial and an underwater one. Specifically, the first phase is only non-propulsive, while the second one is subdivided into a propulsive and a non-propulsive subphases. Thus SR and SL are determined by the duration and distance traveled in each phase. A positive relationship was found between swimming velocity and the duration of the pull phase (Chollet et al., 2008; Keskinen and Komi, 1993), the push phase (Chollet et al., 2008; Keskinen and Komi, 1993) or the propulsive phase (Barbosa et al., 2008b). Conversely, velocity was inversely related to the duration of the entry phase (Lerda and Cardelli, 2003). Furthermore, the work of Chatard et al. (1990) demonstrated that a greater duration of the pull phase increases the time useful for the propulsion and, together with a better gliding position, generates a higher efficiency in swimming thus reducing the energy cost.

All the above reported considerations, however, do not take into account that backstroke is an alternating stroke. Thus, the inter-arm coordination could be one of the key features for increasing the swimming velocity. The coordination index (IdC) (Chollet et al, 2008) quantifies the continuity of the propulsive action of the arms. This index was found to play an important role for the analysis of an athlete's adaptation to different race distances (Schnitzler et al., 2009), but also to have a limited range of variation in backstroke (Seifert and Chollet, 2009). Specifically, coordination showed a smaller role in backstroke than in front crawl swimmers (Seifert and Chollet, 2009).

In order to better understand how SR, SL, phases duration, and IdC are related to velocity in backstroke, a possible solution is to compare kinematic variables of swimmers of different distance specializations. 200-m backstroke athletes swim at a lower velocity with respect to 50-m backstroke athletes of the same level, but are able to maintain the velocity for a longer time. Thus, the different distance specialization may have induced different technical strategies that can be reflected in a different duration of the stroke phases. To the knowledge of the present authors, only two studies compared recently 50-m and 200-m distance swimmers (McCabe et al., 2011; 2012), finding a difference in the pull phase between the two groups but only at front crawl sprint pace.

Thus, the aim of the present study was to compare the kinematic patterns of 200-m distance backstroke swimmers with respect to 50-m distance swimmers, at maximal and sub-maximal velocity, in order to investigate the capacity of the athletes to obtain the maximum velocity in relation to their distance specialization. We hypothesized a more effective relationship between propulsive and non propulsive phases for the 50-m distance swimmers due to the higher capacity to achieve higher velocities.

Methods

Participants

Eighteen highly trained (35 ± 10 km/week) backstrokers were analyzed, including 9 (5 males and 4 females) 50-m

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distance swimmers (50-m DS) and 9 (5 males and 4 females) 200-m distance swimmers (200-m DS), specialized in their preferred distance event for a minimum of 2 years. Their mean (±standard deviation) age, height and body mass were 17.7 ± 2.8 years, 1.73 ± 0.09 m and 65.6 ± 9.7 kg for 50-m DS, and 18.3 ± 5.7 years, 1.77 ± 0.08 m and 68.9 ± 12.5 kg for 200-m DS, respectively. Their skill level was assessed using the result of a race event in their preferred distance, performed during the competitive season and expressed as a percentage of the relevant World Record (Seifert et al., 2007). Male swimmers showed an average racing time of 22.61 s on 50m (n = 5) and 106.11 s on 200 m (n = 5). For women, 25.7 s. on 50 m (n = 4) and 120.2 s (n = 4) on 200 m. Their expertise (% of W.R.) was 76.0 ± 8.1 for 50-m DS and 75.0 ± 8.9 for 200-m DS.

The participants were previously informed about the procedures of the study and signed a written consent to participate. The study was approved by the local review board.

Motor task

The test session was conducted in a 25-m indoor swimming pool (average water temperature 28.0 ± 0.5° C). The testing procedures required two 25-m backstroke swimming trials for each swimmer performed in the same day. The swimmer, after pushing the head wall without a back start, was instructed to perform an underwater gliding shorter than 10 m. No other swimmers were in the same lane. Before each trial, the participants carried out a 20-min warm-up period and habituation to the experimental conditions. The first 25-m trial was performed at maximal velocity (Vmax), the second one at 70% of the previously determined Vmax (V70). Vmax and V70 were chosen to evaluate a 25-m trial with maximal and submaximal effort, respectively (Kjendlie et al., 2004). The V70 velocity, selected as the highest submaximal velocity analyzed in a previous study (Kjendlie et al., 2004), was imposed to the swimmers using light signals produced by an apparatus (MOSES, APLAB, Roma, Italy) placed along the pool edge on the swimmer's side in a way that did not affect the body position and thus the kinematics of swimmers. A passive recovery period of 5-min was carried out between the two 25-m trials, as a previous study (Toubekis et al., 2011) advised a 2-min of interval period.

Data acquisition and analysis

All trials were filmed with two underwater cameras (Sony Hyper Had, TS-6021PSC PAL interlaced, 25 frames/second). The first camera was static and positioned perpendicular to the swimmer's direction on a sagittal view, 12.5 m far away from the start. This camera recorded a complete stroke cycle. The second, dynamic, camera filmed the athlete during five complete consecutive stroke cycles. This latter camera was fixed on a trolley that was able to travel parallel to the pool. Filming the full body of the swimmer along all the 25 m of the pool was possible due to the possibility to see the video online. This camera was used to provide data relevant to the repeatability assessment of the kinematic analysis of the single stroke acquired by the first static camera and was used for two subjects only.

For both cameras, the geometric distortion was corrected by applying a fourth degree polynomial correction technique (Gronenschild, 1997) and a bilinear interpolation, using the Matlab 7 software (MathWorks, Inc., USA). Furthermore, the rotation around camera optical axis, due to the anchorage system, was taken into account and corrected using the swimming pool lane as reference for the horizontal axis.

With a manual tracking of the video recordings, a bidimensional analysis of the arm stroke action was carried out using a commercial software package (Twin pro, SIMI Motion, Germany). Reference anatomical landmarks were fixed on the third head of the metacarpal bone, the right-acromion, and the great trocanther. An experienced operator performed the manual tracking. No further signal processing, i.e. data smoothing and/or filtering, was performed. In order to assess the reliability of the tracking digitations, five trained operators were asked to perform the manual tracking of the third head of the metacarpal bone of one stroke cycle and relevant reliability was calculated (ICC = 0.996). For video acquisitions performed using the static camera, the coordinates of the three landmarks were reported in the swimming pool reference frame, while for the dynamic camera video acquisition the coordinates of the third head of the metacarpal bone were calculated with respect to the great trocanther anatomical landmark.

The swimming velocity was recorded with an encoder (SpeedRT, ApLab Rome) measuring the distance and time through the extraction of a wire coil placed in a rotating sensor and fixed with a belt to the waist of the swimmer. This instrument allowed to record the instantaneous velocity of the swimmer during each phase excluding the underwater phase immediately after the start.

For two athletes, the trajectories of the hand with respect to the great trocanther during the five cycles, acquired with the dynamic camera, were superimposed to verify the repeatability of the arm movement. Mean and standard deviation of the trajectories were evaluated.

Arm stroke movements were divided in six phases (Chollet et al., 2008), each individuated as the time between two events (Figure 1). Entry and catch of the hand in the water is the interval between the first contact of the hand with the water above the head and the catch of arm stroke, i.e. the point just before the first arm backward movement. Pull, is the first of two propulsive phases. It is the interval between the instant in which the hand starts its backward movement and the instant in which the hand is perpendicular to the shoulder. Push is the phase corresponding to the time from the position of the hand below the shoulder to the end of the hand's backward movement. In the sagittal view, the hand lag time is the time in which the hand stays still at the thigh. This is an intermediate phase between the push and the clearing (Colwin, 2002; Maglischo, 2003). Clearing is the interval between the point in which the hand starts its upward movement and the point in which it starts to come out of the water. In the recovery phase the hand is out of the water, and thus that phase is called the above-water phase. It is the interval between the points of the hand water exit end

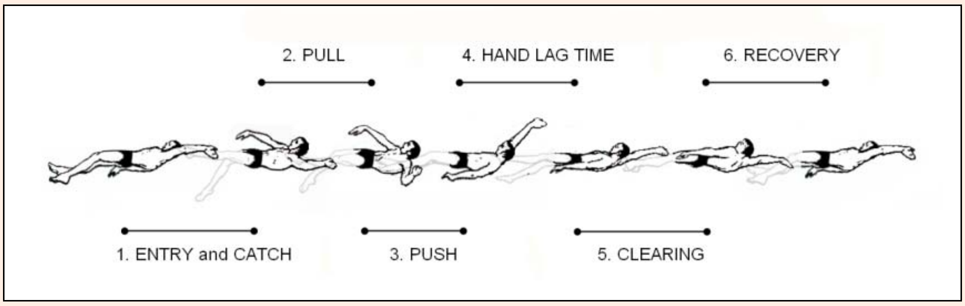

Figure 1. Arm stroke phases in backstroke (classification proposed by Chollet et al., 2008).

re-entry. The absolute duration of each phase was calculated and expressed as a percentage of the total duration of the underwater arm stroke.

The following variables were calculated. Stroke time (ST) was considered as the time required to perform five complete stroke cycles (Arellano et al., 1994). Stroke rate (SR), expressed in strokes per minute, was calculated using the following equation: SR = 60/(ST/5). SL was considered as the distance travelled by the great trocanther through the water in a complete stroke. The mean pulling length was considered as the distance between the point of beginning of propulsion and the point of the end of propulsion. The mean pulling depth was considered as the distance between the entry of the hand in the water and its exit (Smith et al., 1988). Finally, the duration of the arm stroke phases was computed.

From the duration of each phase an IdC (Chollet et al., 2000) was calculated, as follows, individuating three different patterns of coordination: a) the opposition, a coordination model in which the propulsive phase of one arm begins when the propulsive phase of the other arm ends (IdC = 0%); b) the catch-up model, when there is a time delay between the propulsion of the two arms (IdC = -n%); c) the superposition, when the propulsion of the two arms is overlayed (IdC = +n%).

Statistical analysis

All the data are expressed as mean ± SD. Two-way ANOVAs were used to analyze the effects of distance specialization (between-subject factor), swimming velocity (within-subject factor), and their interaction on each dependent variable. Significance was set at $\alpha = 0.05$. All the statistical analysis was performed using SPSS version 14.

Results

Mean and standard deviation of the hand trajectories, with respect to the great trocanther, during the five consecutive cycles of a 50-m DS athlete at maximal and submaximal velocity were reported in Figure 2. Similar results were found for a 200-m DS athlete acquired with the dynamic camera. The maximum standard deviation, among both subjects at both velocities, was 0.161 m for the horizontal direction at 28% of the cycle duration.

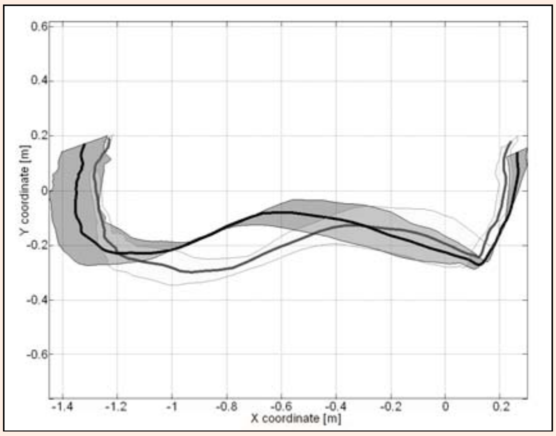

Figure 2. Mean and standard deviation curves for the one 200-m DS at maximal (dark grey) and submaximal (light grey) velocity, in the horizontal (x) and vertical (y) direction of the hand trajectories with respect to the great trochanter.

The velocity, SR, SL, mean pulling length and mean pulling depth data are shown in Table 1. Comparing50-m DS and 200-m DS independently from the velocity, the SR is higher in the swimmers of the 50-m DS group ($F_{1,16} = 8.847$, $p = 0.009$). Comparing Vmax and V70 independently from the distance specialization, SR ($F_{1,16} = 164.688$, $p < 0.001$), velocity ($F_{1,16} = 622.047$, $p < 0.001$) and mean pulling depth ($F_{1,16} = 5.350$, $p = 0.034$) were larger at Vmax. On the contrary, mean pulling length was higher in V70 ($F_{1,16} = 7.346$, $p = 0.015$), independently from the distance specialization.

The IdC and percentage duration of the total

Table 1. Velocity, SR , SL, mean pulling length and depth for each group at maximal (Vmax) and submaximal (V70) velocity, distinguishing 50-m DS from 200-m DS. Data are means (±SD).

Imposed swimming speed	Velocity ($m \cdot s^{-1}$)		Stroke rate ($strokes \cdot min^{-1}$)		Stroke length (m)		Mean pulling length (m)		Mean pulling depth (m)	
	V70	Vmax	V70	Vmax	V70	Vmax	V70	Vmax	V70	Vmax
200-m DS	1.01 (.13)	1.40 (.16)*	28.3 (3.5)	40.0 (2.2)*	2.17 (.45)	2.10 (.19)	.61 (.08)	.54 (.12)*	-.16 (.28)	-.04 (.14)*
50-m DS	1.05 (.13)	1.44 (.16)*	30.7 (2.6)†	45.5 (5.3)*†	2.10 (.38)	1.90 (.12)	.57 (.10)	.55 (.12)*	-.22 (.17)	-.03 (.16)*

* Significant difference with v70, † with 200-m DS group, p < 0.05

Table 2. . Arm stroke phase and IdC for each swimmer, at maximal (Vmax) and submaximal (V70) velocity, distinguishing 50-m DS from 200-m DS. Data are means (±SD).

Imposed swimming speed			200-m DS	50-m DS
Non-propulsive phase	Entry phase (%)	V70	25.2 (5.2)	25.3 (9.4)
		Vmax	26.0 (6.6)	24.0 (6.3)
Propulsive phase	Pull phase (%)	V70	10.8 (4.3)	8.9 (1.9) †
		Vmax	10.2 (2.1)	11.4 (3.6) †
	Push phase (%)	V70	11.0 (3.5)	9.7 (1.5) †
		Vmax	10.5 (1.5)	13.1 (2.6) †
Non-propulsive phase	Hand lag time phase (%)	V70	3.6 (1.5)	4.3 (1.7)
		Vmax	6.0 (2.9) *	6.5 (3.4) *
	Clearing phase (%)	V70	15.7 (3.5)	17.9 (5.3)
		Vmax	12.4 (3.4)	15.5 (5.0)
	Recovery phase (%)	V70	33.4 (4.7)	33.8 (5.3)
		Vmax	34.9 (6.1)	29.5 (2.2)
	Propulsive phase (%)	V70	21.9 (5.7)	18.6 (2.8) †
		Vmax	20.7 (2.4) *	24.5 (3.6) *†
	Non-propulsive phase (%)	V70	78.1 (5.7)	81.4 (2.8) †
		Vmax	79.2 (2.4)	75.5 (3.6) †
	IdC (%)	V70	-6.5 (5.6)	-6.9 (3.2)
		Vmax	-2.7 (4.2) *	-2.1 (3.7) *

* Significant difference with v70, † with 200-m DS group, $p < 0.05$

underwater arm stroke phase are reported in Table 2. Although IdC corresponds at both velocities to the catch-up model, it was higher at Vmax ($F_{1,16}$ = 16.546, p = 0.001) independently from the distance specialization. Comparing Vmax and V70 independently from the distance specialization, the percentage duration of the hand lag ($F_{1,16}$ = 5.920, p = 0.027) and propulsive ($F_{1,16}$ = 6.495, p = 0.021) phase were larger at highest velocity. A significant interaction between velocity and distance specialization was found for the percentage duration of the pull ($F_{1,16}$ = 5.378, p = 0.034) and the push ($F_{1,16}$ = 7.488, p = 0.015), with 50-m DS and 200-m DS respectively showing an increase and a slightly decrease of the relative duration of both these phases with increasing velocity. The effect of interaction was also significant for the percentage duration of the propulsive phase ($F_{1,16}$=14.614, p = 0.001) and the non propulsive phase ($F_{1,16}$ = 14.861, p = 0.001). In fact, at Vmax, 200-m DS tended to decrease the percentage duration of the propulsive phase and then to increase that of the non propulsive phase. An opposite effect was observed in 50-m DS, with higher percentage duration of the propulsive phase at Vmax. Thus, 50-m DS are able to modify the ratio between propulsive and non propulsive phase at different velocities.

The distance covered by the hand, in the different phases, is shown in Table 3. Comparing Vmax and V70 independently from the distance specialization, the distance covered is higher at the lowest velocity in the entry ($F_{1,16}$ = 12.742, p = 0.003) and clearing ($F_{1,16}$ = 12.431, p = 0.003) phase. In order to better analyze graphically the spatial differences among the phases, the trajectory of the hand in the pool was reported in Figures 3 and 4 for a representative subject of the 200-m DS and 50-mDS groups, respectively.

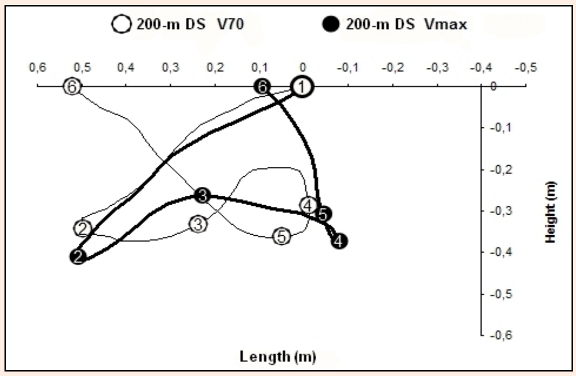

Figure 3. Sagittal view of the arm stroke phases in each trial for one 200-m DS (1-2=Entry, 2=Catch, 2-3=Pull, 3-4=Push, 4-5= Hand lag time, 5-6=Clearing).

Discussion

With the aim to investigate the capacity of the 50-m DS and a 200-m DS to modify the timing of the arm stroke, 18 highly trained athletes were analyzed at maximal and sub-maximal velocity. At the highest velocity, the 50-m DS showed a significant higher duration of the propulsive stroke phase, in both the push and pull phases. On the contrary, the 200-m DS did not show any difference in the duration of the phases. Athletes specialized in sprint distance are able to modify the ratio between propulsive and non propulsive phase at different velocities.

Table 3. Distance covered by the hand on the underwater phase, at maximal (Vmax) and submaximal (V70) velocity, distinguishing 50-m DS from 200-m DS. Data are means (±SD).

Imposed swimming speed	Entry phase (m)		Pull phase (m)		Push phase (m)		Hand lag time phase (m)		Clearing phase (m)	
	V70	Vmax	V70	Vmax	V70	Vmax	V70	Vmax	V70	Vmax
200-m DS	.68 (.22)	.59 (.21)*	.38 (.11)	.32 (.07)	.41 (.08)	.36 (.05)	.12 (.05)	.12 (.05)	.61 (.14)	.47 (.10)*
50-m DS	.62 (.24)	.46 (.08)*	.33 (.08)	.29 (.06)	.38 (.06)	.38 (.08)	.14 (.07)	.14 (.07)	.60 (.16)	.48 (.13)*

* Significant difference with v70

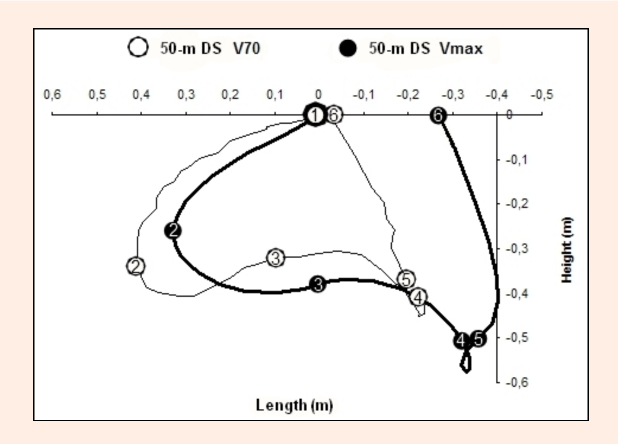

Figure 4. Sagittal view of the arm stroke phases in each trial for one 50-m DS (1-2=Entry, 2=Catch, 2-3=Pull, 3-4=Push, 4-5= Hand lag time, 5-6=Clearing).

The kinematics of backstroke swimmers were observed and quantified by means of underwater camera allowing the quantification of several variables such as ST, SR, SL, mean pulling depth and length, and the duration of the stroke phases. Analyzing two groups of athletes with different event specialization, 50m and 200m, at two velocities, maximal and sub-maximal, permitted to distinguish different ability in modifying the duration of the phases and specifically the propulsive one.

In agreement with previous studies (Craig and Pendergast, 1979; Klentrou and Montpetit, 1992; Pai et al., 1984), a direct relationship between the velocity and SR was found independently from distance specialization (Table 1). In front crawl, similarly, the possibility to reach a high SR (over 50 cycles/min) resulted a key factor for velocity (Seifert et al., 2007). The results of the present work highlighted a better capacity of the 50-m DS compared to the 200-m DS to reach a higher SR. This finding may be explained by a higher mechanical power and muscle strength of the athletes specialized in shorter distance. For all athletes, comparing Vmax to V70, the mean pulling depth showed a displacement opposite with respect to the direction of swimming (Table 1).

The arm stroke timing may influence the capability to reach high velocities and changes, as a function of velocity, in a different way between the 50-m DS and 200-m DS. Spending more time on the pull phase enhances the propulsion time and consequently also the propelling efficiency (Chatard et al., 1990). Thus, 50-m DS improved the arm stroke propulsion phase time and decreased the non propulsive one (Table 2). This determined a more efficient relationship between the propulsive and non propulsive phases. Specifically, both the push and pull phases showed a different behaviour between the 50-m DS and 200-m DS. As pointed out in previous works analysing the front crawl (Chollet et al., 2000; Keskinen and Komi, 1993), an increase of the duration of the push and the pull phases is associated to an increase in velocity. The ability to express an optimal timing during the different phases of the arm stroke seems to be a fundamental factor for the performance. In our analysis, 50-m DS were more able than 200-m DS in changing the timing of the underwater phases, giving more importance to the propulsive phase. Chollet et al. (2008) also made a similar finding in the backstroke: a higher duration of the push and pull propulsive phases and a lower entry and catch non propulsive phases was found in swimmers able to reach higher velocities. These results can be explained by a different motor control of the 50-m DS with respect to the 200-m DS due to the fact that sprint swimmers were more trained at maximum velocities, while long distance swimmers were trained in aerobic exercise, as observed by (Seifert et al. 2010).

Regarding the IdC (Table 2), the analyzed swimmers tended to modify their arm coordination as a function of the arm stroke velocity and SR enhancement towards a reduction of the lag time between the propulsive phase of an arm and the other as observed previously (Chollet et al., 2000). The continuity of the arms propulsive action may not be a key factor for the backstroke performance. All the participants of the present study showed a lag time between the propulsion of one arm and the other, at both considered velocities. This result substantiates a previous finding where the catch-up model was considered as the only possible coordination model for backstroke (Lerda and Cardelli, 2003). Probably, this finding is related to a more limited physiological motion on the backstroke with respect to the other three strokes due to anatomical constraints. As a mechanical consequence of this style, the backstrokers have to use the catch-up coordination. In this model, when one hand is at the beginning of the exit phase, the other one is at the half of the entry phase, adding some time between the two propulsive phases and removing the continuity of the propulsive action of the arms. All the swimmers showed a trend to decrease this lag time with the increase of velocity, in agreement to what shown by Seifert et al. (2007).

No differences were observed in the distance covered by the hand between the two groups (Table 3). The distance covered by the hand decreased at Vmax in the entry and clearing phases, independently from the distance specialization. This result becomes especially significant when associated with the reduction of the percentage duration of the non propulsive phase, found only in the 50-m DS. Different stroke organization may be enhanced at higher velocities due to the relevant higher aquatic resistance (Seifert et al, 2010). Thus, the kinematical changes observed between 50-m DS and 200-m DS may be associated to a combined effect of different motor control and muscle strength of the sprinter with respect to the long distance swimmers.

In the present work, the study was limited to the bidimensional analysis of the kinematics, thus the motions on the frontal and coronal plane was not taken into account. Furthermore, a more complete kinematic analysis using a biomechanical model of the upper limb not limited to the hand and acromion trajectories could highlighted further differences between the two groups analysed.

The main biomechanical patterns of arm stroke in backstroke have been analysed comparing 50-m DS with 200-m DS. The most important finding was the difference between the 200-m DS and 50-m DS in the ability to modify the duration of arm stroke phases. A longer duration of the propulsive phase was advantageous for swimming velocity. The findings suggest that it would be advantageous for coaches to optimize the timing of the propulsive/non-propulsive phases of the arm stroke in backstroke. In this respect, training sessions with different coordination models and/or timing may help the athletes to explore a wide range of motor control possibilities and use the more appropriate one at different velocities. Future perspectives involve three-dimensional analysis of the arm stroke, focusing on the individual technical adaptations to different velocities and their relationships with the swimming performance.

Conclusion

Backstrokers enhanced stroke rate when the velocity increased, furthermore the 50-m DS showed a higher stroke rate with respect to the 200-m DS. The present results showed that, when the velocity increased from submaximal to the maximal, the 50-m DS improved the arm stroke propulsion phase time and decreased the non-propulsive one. Specifically, both the push and the pull phases showed a different behaviour between the 50-m DS and the 200-m DS and determined a more efficient relationship between the propulsive and non-propulsive phases in the 50-m DS swimmers. The 50-m DS seemed to be more able to modify the arm stroke phases duration when increasing the swimming velocity in backstroke. On the contrary, the 200-m DS swimmers showed similar behaviour at maximal and submaximal velocities regarding the timing. This finding enhanced a lower adaptation capability of swimmers specialized in 200-m distance in modifying the ratio between propulsive and non propulsive phases.

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Key points

- The 50-m DS are able to find an optimal timing among the stroke phases increasing the duration of the propulsive phase.
- The 50-m DS, when increasing the swimming velocity, show a more efficient relationship between propulsive and non propulsive phases with respect to the 200-m DS.
- Both pull and push phases are key factors for increasing the duration of the propulsive phase for the 50-m DS.

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