Journal of Science and Medicine in Sport 25 (2022) 95–100

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Original research

Arm–leg coordination during the underwater pull-out sequence in the 50, 100 and 200 m breaststroke start

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ARTICLE INFO

Article history:
Received 20 March 2021
Received in revised form 20 July 2021
Accepted 4 August 2021
Available online 12 August 2021

Keywords:
Swimming
Biomechanics
Performance analysis
Underwater sequence
Glide
Motor control

ABSTRACT

Objectives: To investigate the arm–leg coordination from different perspectives of motor control during the underwater start sequence to understand whether differences exist between the three competitive breaststroke swimming events.
Design: Cross-sectional study.
Methods: Forty-one breaststroke races (with race times relative to the world record): 50-meter ($n = 14$, 87.6%), 100-meter (n = 14, 88.5%) and 200-meter ($n = 13$, 85.4%) were recorded. A race analysis system tracked the two-dimensional displacement of the head. Key points from the underwater start sequence were obtained from notational analysis in order to compute seven time-gaps and four phases to assess the arm–leg coordination and timing of the dolphin kick. A one-way ANOVA with Bonferroni post-hoc correction was used to assess differences between the time gaps and phases for the three events.
Results: Differences between the three events were found for total underwater glide, and the first (T0) and second (T1) major glide phase. No differences between the events were found in relative duration and distance for the time gaps related to arm–leg coordination (T1–3, T4, T6) and timing of the dolphin kick (T4–5) during the underwater start sequence.
Conclusions: The arm–leg coordination and timing of the dolphin kick showed no difference between the events, but the total underwater glide duration was longer in both the 100- and 200-meter compared with the 50-meter start. This shows that swimmers did not change the complex inter-limb coordination between the competitive events, but only modified the least complex movement, gliding, to adapt to the swimming speed of the respective events.

Practical implications

- There is no need to practice different modes of inter-limb coordination for the underwater start sequence between the three competitive events.
- Longer underwater gliding should be utilized as the event gets longer.
- While there is no overlap between arm and leg propulsion on average, the observed inter-individual differences might encourage coaches to monitor the best individual strategy to manage the underwater start sequence.
- High inter-individual variability suggests to individually manage the time between the end of the dolphin kick and the beginning of the arm pull-out.

1. Introduction

Previous research has highlighted the importance of the start segment in swimming races and the start time can account for approximately 11.5% in the 100-meter short and long course breaststroke,[1–3] and 5.5% in the 200-meter long course.[3] While no one has investigated the time contribution in the 50-meter breaststroke, the contribution in sprint events (e.g. 50-meter front crawl) was 26.1%.[4] A swimming start is often defined as the first 15 m of the race, from the starting signal until the head breaks the 15-meter mark.[2,5,6] While breaststroke does not have a limitation in the length of the underwater distance as the three other strokes do (15 m), it is still reasonable to consider the start as the first 15 m of the race. This is because the breakout distance has been reported to be approximately 13–14.5 m depending on the event's distance and the underwater phase will therefore be an important part of the breaststroke start time.[2,7,8]

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https://doi.org/10.1016/j.jsams.2021.08.006

Breaststroke is the only competitive stroke with an underwater pull-out sequence during the start. The three other competitive strokes are primarily characterized by an underwater dolphin kicking motion. Therefore, it seems important to coordinate the underwater arm and leg movements together with glide phases to minimize resistance and maximize speed. Previously a single butterfly kick was permitted by the rules only during the first arm stroke (which begins with the separation of the hands), followed by a breaststroke kick. With the change in 2015 a single butterfly kick is permitted now at any time prior to the first breaststroke kick after the start and is not restricted to during the first arm stroke.[9] During this underwater sequence, little is known regarding the coordination between the arms and legs, as well as the timing of the dolphin kick since it could occur before, together or after the arm pull-out.

Only one study investigated the arm–leg coordination during the breaststroke start (when the dolphin kick was not permitted during the underwater sequence) and found that the international swimmer spent more time for gliding with arms close to the thighs than national swimmers, and the whole population started leg propulsion before completing arm recovery.[10] Two other studies investigated the placement of the dolphin kick without considering the arm–leg coordination during the start sequence.[10,11] While one study identified a shorter start time in female breaststrokers with an early placement of the dolphin kick, which was not the case for male breaststrokers.[10] The other study used computational simulation modeling with one participant and found that the optimal placement of the dolphin kick was 0.4 s earlier than the arm pull-out.[11] Since the underwater phase is complex, it is reasonable to hypothesize that the timing between the dolphin kick and the arm pull-out could influence the arm and leg actions and glide phases, which should be further investigated.

During whole-body breaststroke swimming, the glide decreased from −25.8 to −10.4% when speed increased from 200-meter to 50-meter paces, while the arm–leg coordination during propulsion and recovery did not change with the increase in speed.[12] However, the underwater pull-out is quite different from regular breaststroke as it constitutes a more extended and presumably more propulsive phase of the arms (push from the shoulders to the thighs) and some glide time within the complete stroke with hands at the side.[13] It is currently unclear whether the arm–leg coordination during the underwater start would show a similar change with the increase/decrease in speed to the whole-body breaststroke swimming. Moreover, swimming at higher speeds (i.e. 50- vs.100-, vs. 200 m) would increase time pressure to perform these movements and would make its organization and control more complex, which should be investigated to optimize the effectiveness of the underwater sequence. Therefore, coordination during the underwater sequence of the breaststroke start should be addressed from different perspectives of motor control; the more complex overlap between arm and leg movements (i.e. both limbs simultaneously perform a propulsive or resistive movement), less complex continuous coordination (i.e. where the upper or lower limb perform the same type of active [resistive or propulsive] movement continuously without a time gap or overlap), and the simplest form of movement — gliding (i.e. where both limbs are extended and perform no active movement).

The purposes of this study were to investigate the arm–leg coordination from different perspectives of motor control and the timing of the dolphin kick with the arm pull-out during the underwater start sequence to understand whether differences exist in the coordination between the three competitive race events, the 50-, 100- and 200-meter breaststroke. The hypothesis was that overlap and continuous coordination would be similar, but a difference would occur with shorter glide phases and higher speeds for the shorter race events.

2. Methods

Forty-one international or national level short-course 50-meter ($n = 14$), 100-meter (n = 14) and 200-meter ($n = 13$) breaststroke races were recorded. There were no significant differences between the groups according to the international point system for performance (FINA-points): 674.93 ± 92.23, 695.50 ± 86.03 and 627.38 ± 93.29 points for 50-, 100- and 200-m, respectively. The study was approved by the local ethical committee and the National Data Protection Agency for Research in accordance with the Declaration of Helsinki. Participants were informed about procedures, benefits and potential risks of the study orally and in writing. Thereafter, participants or the legal guardian (for minors) provided written informed consent prior to participation.

Each race was recorded by the AIM race analysis system (AIMsys Sweden AB, Lund, Sweden) synchronized with an electronic Omega timing system (Swiss Timing, Bienne, Switzerland). The system does not require swimmers to wear any device besides a yellow silicon cap (used for movement recognition). Each race was captured using ten stationary cameras, whereof five were placed above and five underneath the water surface alongside the 25-meter swimming pool. The first camera was placed 2.5 m from the starting wall, and thereafter each camera was placed 5 m apart. The sampling frequency was 50 Hz. Calibration resulted in a mean error of 2.0 pixels, corresponding to a 0.025° angular and 0.6 cm linear error. On race completion, the automatic post-processing produced a panning video file (MPEG-4 Part 14) and a synchronized Excel sheet containing the center of the head displacement data relative to the global coordinate system, which were used for further analysis. For more details regarding the set-up, calibration and post-processing, see Olstad et al.[2] and Haner et al.[14]

Key points of the underwater start sequence (from when the hands enter the water until the head regains the water surface) were qualitatively analyzed by five experts (>30 h of experience)[15] randomly paired using a blinded technique based on underwater side and aerial views, previously used in breaststroke,[16,17] and validated for front crawl.[15] If the difference between the two experts did not exceed 0.04 s, the mean was accepted to validate the key point. When the difference was above 0.04 s, the two experts discussed their differences and performed a new assessment of the key point until the difference was ≤0.04 s.

The performance outcomes were determined as the time and distance traveled by the head and the mean speed during the underwater sequence. A model including the underwater sequence with seven key points for arm actions (A- to F) and eight for leg actions (0 to 7), together with seven time-gaps (T0 to T6) were measured and shown in Fig. 1. All time-gaps were expressed in relative duration and distance in percentage of the active underwater sequence (defined as the duration between the beginning of the first active motion and the head breakout), except for T0 which occurred prior to any active arm and leg movements and is expressed in percentage of the underwater start sequence (from the feet entry following the dive to the head breakout).

Four time-gaps (T0, T1, T4 and T6) were related to glide phases. When $T0 > 0$, there was an initial glide phase between the feet entering the water and the first active arm or leg action. If $T4 > 0$, there was a glide between the dolphin kick and the start of the arm pull-out. When $T1 > 0$, there was a glide following the arm pull-out with arms at the side, and if $T6 > 0$, there was a glide between the end of knee extension in the breaststroke kick and prior to the start of the first arm action of the first swimming stroke.

The time-gaps of T4 and T5 were used to measure the coordination between the dolphin kick and the arm pull-out. T4 was between the end of the dolphin kick and the beginning of the arm pull-out, while T5 was between the start of the dolphin kick and the end of the arm pull-out. Therefore, if $T4 > 0$ and $T5 < 0$, the dolphin kick occurred before the arm pull-out; if $T5 > 0$, it occurred after the arm pull-out; and overlapped the arm pull-out if T4 and $T5 < 0$.

The time-gaps of T1–T3 were used to assess the arm–leg coordination during the active underwater sequence. As noted above, T1 was identified as glide duration with arms at the side, while T2 identified the synchronization between the beginning of arm and leg recovery

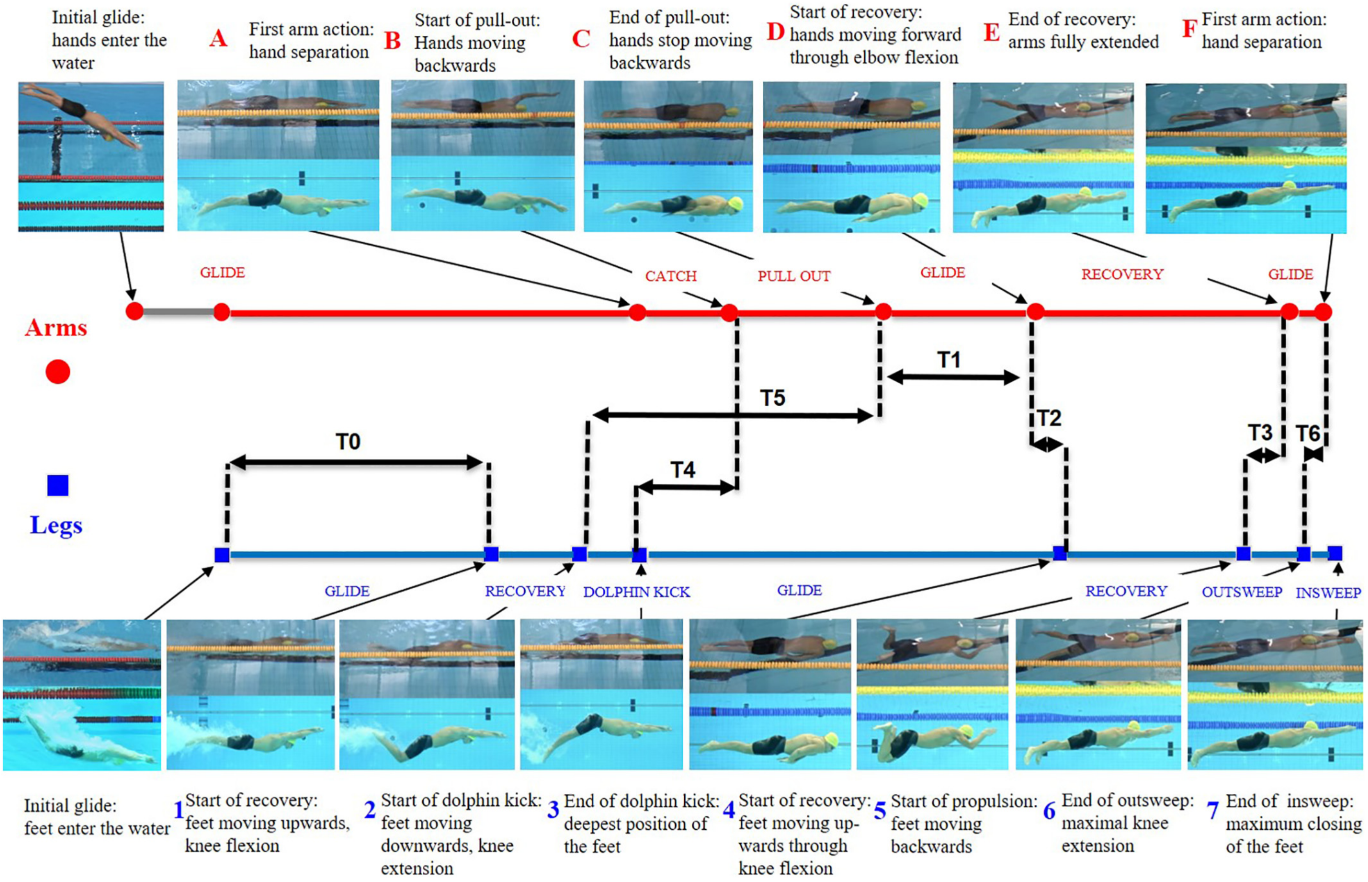

Fig. 1. Key points, phases and time-gaps of the underwater start sequence of the arms and legs.
Note: The example is provided from the mean values of the 50-meter breaststroke races.
(A) First arm action, when the hands start to separate to break the initial streamlined position, (B) Start of pull-out, when the hands start to move backwards following the initial streamlined position, (C) End of pull-out, when the hands stop moving backwards at the thigh, (D) Start of the recovery, when the elbows start flexing and the hands start moving forward from the thigh, (E) End of recovery, when the arms are fully extended to make the second streamlined position before the breakout, (F) The first arm action following the second streamlined glide (beginning of the first cycle of the surface swimming); (1) Start of dolphin kick recovery, when the knees start flexing and feet go upward, (2) Start of dolphin kick, when the knees start extending and the feet move downward, (3) End of dolphin kick, when the feet reach their deepest position, (4) Start of leg recovery, when the knees start flexing and the feet go upward, (5) Start of leg propulsion, when the feet move backward after the knees show their maximum flexion, (6) End of outsweep, when the legs are fully extended, (7) End of insweep, when the feet are maximally closed after the leg extension, (T0) Initial glide, from feet entering the water until the first active arm or leg action, (T1) Glide phase, following the arm pull-out with arms at the side until the beginning of arm recovery, (T2) Coordination between the beginning of arm and leg recovery, (T3) Coordination between the end of arm and leg recovery, (T4) Coordination between the dolphin kick and the start of the arm pull-out, (T5) Coordination between the start of the dolphin kick and the end of the arm pull-out, (T6) Coordination between the end of knee extension in the breaststroke kick and the start of the first arm action of the first swimming stroke.

and T3 the synchronization between the end of arm and leg recovery. If T2 = 0, the arm and leg recovery started simultaneously; if <0 or > 0, the arm recovery started respectively earlier or later. When T3 = 0, the arm and leg recovery ended simultaneously; if <0, the leg propulsion started prior to the finish of arm recovery and > 0 shows the legs were still in recovery while the arm recovery was completed.

The relative duration and distance during the underwater sequence and the mean speed (m/s) of the head during three propulsive and one non-propulsive phases were also quantified. These include the propulsive dolphin kick (from the highest to the deepest feet position), the arm pull-out (where the hands moved backwards), the breaststroke kick (from start of leg propulsion until the end of the feet insweep) and the total underwater glide duration (the sum of T0, T1, T4 and T6).

In addition, kinematic performance variables of the start segment were analyzed and are previously described by Olstad et al.[2]

A descriptive analysis (mean and one standard deviation) was calculated for all start performance variables, time gaps and phases. The different time gaps and phases were normalized to the duration and distance of the active underwater sequence. A Shapiro-Wilk test was used to assess the normality of the distribution for all variables. A one-way ANOVA with Bonferroni post-hoc correction was used to assess differences between the time gaps and phases for the 50, 100 and 200-meter event. Significance level was $p < .05$. All statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) version 24.0 (IBM Corp, Armonk, NY, USA) and Microsoft Excel 2010 (Microsoft Corp, Redmond, WA, USA).

3. Results

No differences between the 50-, 100- and 200-meter breaststroke start were found in the relative duration and distance for the time gaps related to arm–leg coordination (T1–3) and timing of the dolphin kick (T4–5) during the active underwater sequence. However, differences between the events were found in the relative glide distance (T1) and mean speed for glide T0 and T1. Differences were also found between the events in the dolphin kick mean speed, arm pull-out duration and distance, total underwater glide duration, distance and mean speed, the active underwater sequence duration and mean speed and for the total underwater phase duration, distance and mean speed. For detailed results, see Table 1.

Descriptive statistics of the start segment are presented in Table 2 where the breakout time was longer in the 200-meter compared with both 50- and 100-meter, but the breakout distance was similar. The transition velocity from the active underwater sequence to the first swimming cycle was also lower in the 200-meter compared with both 50- and 100-meter.

Table 1
Relative duration and distance traveled by the head (in % of the active underwater sequence) for the seven time-gaps and phases, and the mean head speed during the phases.

Distance	T0*	T1	T2	T3	T4	T5	T6	Dolphin kick	Arm pull-out	Total underwater glide	Active underwater sequence	Underwater start sequence
Duration (%)										(s)	(s)	(s)
ANOVA	$F = 1.06$ $p = .356$ $\eta^2 = 0.053$	$F = 2.03$ $p = .146$ $\eta^2 = 0.096$	$F = 1.65$ $p = .206$ $\eta^2 = 0.080$	$F = 0.16$ $p = .854$ $\eta^2 = 0.008$	$F = 1.00$ $p = .377$ $\eta^2 = 0.051$	$F = 2.86$ $p = .069$ $\eta^2 = 0.131$	$F = 1.81$ $p = .178$ $\eta^2 = 0.091$	$F = 0.84$ $p = .438$ $\eta^2 = 0.042$	$F = 3.94$ **$p = .028$** $\eta^2 = 0.172$	$F = 8.75$ **$p = .001$** $\eta^2 = 0.315$	$F = 7.70$ **$p = .002$** $\eta^2 = 0.288$	$F = 12.71$ **$p < .001$** $\eta^2 = 0.401$
50 m	23.6 ± 5.2	16.5 ± 6.8	−4.2 ± 4.8	−4.2 ± 1.4	12.1 ± 7.3	−34.5 ± 8.2	2.5 ± 4.4	5.5 ± 1.0	16.9 ± 2.9^{a}	2.05 ± 0.35^{a}	3.32 ± 0.40	4.34 ± 0.38
100 m	26.8 ± 5.6	21.0 ± 4.8	−8.1 ± 6.8	−4.4 ± 1.3	8.6 ± 10.0	−27.9 ± 10.2	6.1 ± 6.0	5.0 ± 0.8	14.3 ± 2.1	2.49 ± 0.35	3.42 ± 0.30^{b}	4.69 ± 0.39^{b}
200 m	25.0 ± 6.3	21.3 ± 9.0	−6.7 ± 5.5	−4.2 ± 0.9	8.1 ± 5.6	−28.2 ± 4.9	5.8 ± 5.4	5.1 ± 1.2	15.6 ± 2.2	2.68 ± 0.51^{c}	3.96 ± 0.61^{c}	5.27 ± 0.65^{c}
Distance (%)										(m)	(m)	(m)
ANOVA	$F = 1.19$ $p = .316$ $\eta^2 = 0.059$	$F = 5.05$ **$p = .011$** $\eta^2 = 0.210$	$F = 1.27$ $p = .293$ $\eta^2 = 0.063$	$F = 1.04$ $p = .365$ $\eta^2 = 0.052$	$F = 0.90$ $p = .416$ $\eta^2 = 0.010$	$F = 2.72$ $p = .079$ $\eta^2 = 0.125$	$F = 0.76$ $p = .475$ $\eta^2 = 0.043$	$F = 1.25$ $p = .298$ $\eta^2 = 0.062$	$F = 8.08$ **$p = .001$** $\eta^2 = 0.298$	$F = 3.36$ **$p = .045$** $\eta^2 = 0.150$	$F = 1.30$ $p = .286$ $\eta^2 = 0.064$	$F = 5.12$ **$p = .011$** $\eta^2 = 0.212$
50 m	35.1 ± 5.8	19.1 ± 7.4	4.8 ± 4.3	2.4 ± 0.9	13.8 ± 6.7	42.2 ± 8.3	5.8 ± 2.4	7.1 ± 1.1	21.8 ± 3.5	4.99 ± 0.79^{a}	5.33 ± 0.54	8.24 ± 0.70
100 m	38.6 ± 5.6	24.9 ± 6.0	7.3 ± 4.9	2.7 ± 1.0	13.4 ± 6.9	34.6 ± 11.9	7.0 ± 1.7	6.4 ± 1.2	18.7 ± 2.8^{b}	5.81 ± 0.89	5.36 ± 0.52	8.76 ± 0.69
200 m	36.5 ± 6.8	28.3 ± 9.4^{c}	7.7 ± 6.3	2.9 ± 0.9	12.3 ± 6.4	42.7 ± 10.0	7.3 ± 4.4	6.4 ± 1.7	23.9 ± 3.9	5.71 ± 1.04	5.00 ± 0.83	9.24 ± 1.03^{c}
Speed ($m \cdot s^{-1}$)												
ANOVA	$F = 6.28$ **$p = .004$** $\eta^2 = 0.248$	$F = 6.01$ **$p = .005$** $\eta^2 = 0.240$						$F = 19.68$ **$p < .001$** $\eta^2 = 0.509$	$F = 3.05$ $p = .059$ $\eta^2 = 0.138$	$F = 5.74$ **$p = .007$** $\eta^2 = 0.232$	$F = 35.89$ **$p < .001$** $\eta^2 = 0.654$	$F = 5.16$ **$p = .010$** $\eta^2 = 0.213$
50 m	2.85 ± 0.14	1.89 ± 0.16						2.09 ± 0.14	2.09 ± 0.12	2.46 ± 0.30	1.61 ± 0.11	1.90 ± 0.13
100 m	2.73 ± 0.21	1.85 ± 0.10^{b}						1.99 ± 0.22^{b}	2.05 ± 0.08	2.34 ± 0.26	1.56 ± 0.07^{b}	1.86 ± 0.09
200 m	2.60 ± 0.18^{c}	1.73 ± 0.09^{c}						1.59 ± 0.28^{c}	1.95 ± 0.23	2.14 ± 0.17^{c}	1.27 ± 0.15^{c}	1.76 ± 0.13^{c}

Notes: * T0 occurs prior to the active underwater sequence and is therefore in relative % of the underwater start sequence. Significant difference $p < .05$ (**bold**) between: 50 and 100 m^{a}, 100 and 200 m^{b} and 200 and 50 m^{c}. η^2 = Eta squared.

4. Discussion

The purposes of this study were to investigate the arm–leg coordination and the timing of the dolphin kick during the underwater start sequence between three competitive race events: the 50-, 100- and 200-meter breaststroke. No alterations were present for the inter-limb coordination between the events, but the total underwater glide duration, distance and speed were different, which confirmed the initial hypotheses. Also, the dolphin kick started and finished before the arm pull-out regardless of the event.

The present study found a higher propulsive continuity between the upper and lower limbs that was mostly related to a change in the glide time rather than a change in the inter-limb coordination between the timing of the arm and leg recoveries. This was reasonable, as from the perspective of motor control, it is less complex to adapt glide duration where both arms and legs are extended and perform no active movements than changing the inter-limb coordination where both limbs are performing an active movement (propulsive and/or resistive). A similar result was also found in regular breaststroke swimming where the glide decreased while the time gaps related to arm and leg recoveries did not significantly change with an increase in speed.[12]

Gliding was a major part of the underwater sequence for all three events (duration between 47 and 53% and the distance covered between 61 and 67%). Out of the four phases related to gliding (T0, T1, T4 and T6) during the underwater start sequence, T0 is the first glide with the body in a fully streamlined position, and T1 is the second major gliding phase where the arms are at the thighs after the underwater arm pull-out. The relative duration was similar between the events for both T0 and T1, with more time spent and a longer distance covered in T0 than T1. This might be related to the first gliding position being more streamlined than the second, allowing lower drag force and body cross-sectional values for the same range of speeds.[18,19] Another explanation can also be related to the initial velocity being higher in T0 since the swimmers are entering T0 from an aerial dive. A practical consequence is, therefore, to emphasize spending more time during the first gliding phase after the start, where the need for body position control is of higher importance compared with the second one. For T0, the mean speed was lower in the 200-meter start compared with the 50-meter start, and for T1, it was lower compared with both the 50- and 100-meter. It has been suggested that the first glide should not exceed 6-meter since this could produce a significant loss of speed due to drag.[20] In this study, T0 covered an actual distance of 2.91 ± 0.61 m for the 50-meter and 3.38 ± 0.74 m for the 200-meter, both well underneath the recommended maximum distance. Therefore, another recommendation (the glide phase should be maintained as long as the speed is higher than the surface swimming speed)[18,19,21] can explain the lower speed for both T0 and T1 in the 200-meter start because the required surface swimming speed is lower in a 200-meter than in a 50-meter race.

Table 2
Descriptive statistics (mean ± one standard deviation) of the start segment with underlying components.

Segments and factors	50 m	100 m	200 m	*ANOVA*
15 m start time (s)	7.37 ± 0.53	7.37 ± 0.46^{b}	7.88 ± 0.58	$F = 3.86$, **$p = .030$**, $\eta^2 = 0.169$
Block time (s)	0.70 ± 0.05	0.69 ± 0.05	0.70 ± 0.05	$F = 0.11$, $p = .896$, $\eta^2 = 0.006$
Flight time (s)	0.38 ± 0.06	0.38 ± 0.05	0.39 ± 0.05	$F = 0.07$, $p = .931$, $\eta^2 = 0.004$
Flight distance (m)	3.22 ± 0.22	3.21 ± 0.21	3.08 ± 0.22	$F = 1.76$, $p = .187$, $\eta^2 = 0.085$
Peak velocity (m/s)	4.68 ± 0.21	4.71 ± 0.27	4.52 ± 0.31	$F = 1.80$, $p = .179$, $\eta^2 = 0.087$
Breakout time (s)	5.78 ± 0.37	6.14 ± 0.37^{b}	6.71 ± 0.63^{c}	$F = 11.73$, **$p < .001$**, $\eta^2 = 0.382$
Breakout distance (m)	12.80 ± 0.88	13.27 ± 0.82	13.57 ± 1.16	$F = 2.09$, $p = .138$, $\eta^2 = 0.099$
Underwater average speed (m/s)	2.03 ± 0.13	1.99 ± 0.10^{b}	1.87 ± 0.13^{c}	$F = 6.72$, **$p = .003$**, $\eta^2 = 0.261$
Transition velocity (m/s)	1.39 ± 0.10	1.42 ± 0.09^{b}	1.29 ± 0.12^{c}	$F = 5.35$, **$p = .009$**, $\eta^2 = 0.220$
Transition cycle length (m/cycle)	1.57 ± 0.17	1.66 ± 0.13^{b}	1.94 ± 0.37^{c}	$F = 7.57$, **$p = .002$**, $\eta^2 = 0.285$
Transition cycle rate (cycles/min)	53.71 ± 5.56	51.47 ± 3.80^{b}	40.82 ± 5.96^{c}	$F = 21.94$, **$p < .001$**, $\eta^2 = 0.536$

Notes: Significant difference $p < .05$ (**bold**) between: 50 and 100 m^{a}, 100 and 200 m^{b} and 200 and 50 m^{c}. η^2 = Eta squared.

Mean T4 showed that the end of the dolphin kick occurred before the beginning of the arm pull-out (T4 > 0) regardless of the event. This is supported by the findings that the first gliding phase of the underwater sequence possess the most hydrodynamic body position,[18,19] meaning that it is beneficial to initiate and complete the dolphin kick with this position to maximize the velocity generated by the kick. The relative T4 duration was 12.1–8.6-8.1% in 3.32–3.42-3.96 s of the active underwater sequence. That means the absolute T4 duration was around 0.40, 0.30, 0.31 s for the 50-, 100-, and 200-meter respectively, which supports the findings of the computational simulation modeling case study where it was advised performing the dolphin kick 0.4 s earlier than the arm pull-out. This suggestion based on the simulation can also explain why T4 was much shorter compared with T0, despite that both gliding phases are performed with a similar streamlined position. On the other hand, the large standard deviation in T4 indicates that some swimmers initiated the arm pull-out before the completion of the dolphin kick. This shows that while there was no difference in the timing of the dolphin kick during the start between the three events, there were still individual differences. It is unclear whether the 0.4 s gap is indeed an optimal timing (but swimmers in the present study have not gained the skill), or the optimal timing is individually different. In the latter case, even the initiation of the arm pull-out before the completion of the dolphin kick could be an optimal timing for some swimmers. Therefore, either way, there still might be room for optimizing the coordination between the dolphin kick and the arm pull-out in breaststroke swimming, and further study, such as an intervention research, would be necessary to solve this question.

In the present study, T6 was addressed as another gliding phase. Despite the positive mean T6 duration in all distances (showing that T6 was a gliding phase in general), the high standard deviation indicates that some races had a negative T6, particularly 50 m. This means a propulsive overlap between the breaststroke kick and the first swimming arm-pull. In whole-body breaststroke, one study has reported T6 > 0 in all breaststroke events,[12] while another study found a propulsive overlap which decreased in longer events.[22] This type of coordination requires high energy expenditure during swimming as both the upper and lower limbs are not in a streamlined position,[23] and is performed by only some top-level sprint swimmers.[12] However, the lack of propulsive overlap between the arms and legs (T6) identified in this study for all three events can be related to the difference in the body traveling direction compared with whole-body breaststroke. During surface swimming, swimmers glide forward and can control the head breakout (in each stroke cycle) depending on the glide duration and arm–leg motions. On the contrary, during the start the body is traveling upwards, so the timing of the arm–leg motions needs to be coordinated with the head breakout. In other words, the mechanism might be opposite. Swimmers might control their head breakout timing (prioritizing the glide, arm–leg motions) during regular swimming, but during the start, they might have to control the arm–leg coordination (prioritizing the timing of head breakout).

In the present study, we highlighted general characteristics of underwater motion in breaststroke races from different perspectives of motor control. However, we did not assess how they affect race performance. Therefore, future studies should investigate whether a propulsive overlap in T6 will have a positive effect on the start performance or whether it is just generating additional drag, and how the initiation of the arm pull-out influences the coordination with the dolphin kick (T4) and the start performance.

5. Conclusion

The arm–leg coordination and timing of the dolphin kick showed no difference between the events, but the total underwater glide duration was longer in both the 100- and 200-meter compared with the 50-meter start. From the perspective of motor control, this shows that swimmers did not change the complex inter-limb coordination between the competitive events, but only modified the least complex movement to control (gliding) to adapt to the swimming speed of the respective events.

Funding information

This work was supported by the Portuguese Foundation for Science and Technology, I.P. under Grant UID04045/2021, the Institutional developing project under grant RP 902025009 of Brno University of Technology, Czech Republic, and the French National Agency of Research under Grant ANR-19-STHP-0004, NePTUNE project.

Declaration of interest statement

None.

Confirmation of ethical compliance

The study was reviewed and approved by the local ethical committee at the Norwegian School of Sport Sciences, approval number 47 - 060218-200318 in accordance with the Declaration of Helsinki. It was also reviewed and approved by the National Data Protection Agency for Research, approval number 58650. Participants were informed about procedures, benefits and potential risks of the study orally and in writing before giving their written informed consent prior to participation, the legal guardian (for minors).

Acknowledgments

The authors thank the swimmers and coaches for their collaboration and commitment to this study.

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