Modelling spatial–temporal and coordinative parameters in swimming

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Abstract

This study modelled the changes in spatial–temporal and coordinative parameters through race paces in the four swimming strokes. The arm and leg phases in simultaneous strokes (butterfly and breaststroke) and the inter-arm phases in alternating strokes (crawl and backstroke) were identified by video analysis to calculate the time gaps between propulsive phases. The relationships among velocity, stroke rate, stroke length and coordination were modelled by polynomial regression. Twelve elite male swimmers swam at four race paces. Quadratic regression modelled the changes in spatial–temporal and coordinative parameters with velocity increases for all four strokes. First, the quadratic regression between coordination and velocity showed changes common to all four strokes. Notably, the time gaps between the key points defining the beginning and end of the stroke phases decreased with increases in velocity, which led to decreases in glide times and increases in the continuity between propulsive phases. Conjointly, the quadratic regression among stroke rate, stroke length and velocity was similar to the changes in coordination, suggesting that these parameters may influence coordination. The main practical application for coaches and scientists is that ineffective time gaps can be distinguished from those that simply reflect an individual swimmer’s profile by monitoring the glide times within a stroke cycle. In the case of ineffective time gaps, targeted training could improve the swimmer’s management of glide time.

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1. Introduction

Technical performance in swimming has traditionally been assessed by analysing the changes in and management of velocity, stroke rate and stroke length. Based on the different race paces in the four strokes, Craig and Pendergast and Hay modelled the relationships between stroke rate and velocity and between stroke length and velocity by quadratic regression. However, this calculation did not provide information on the effectiveness of motor organisation.

Inter-limb coordination can be analysed to assess motor organisation. Chollet et al. proposed the Index of Coordination (IdC) to assess right to left arm coordination in front crawl. The IdC is a measure of the time gap between the propulsive phases of the two arms and corresponds to one of three coordination modes (catch-up, opposition and superposition) in relation with race paces. Seifert et al. then showed that sprint specialists switched from catch-up coordination in slow paces to their preferential sprint pattern, superposition mode in fast paces. In the backstroke, which is the other alternating stroke, no change in coordination mode with increasing paces was noted, most likely because shoulder flexibility is limited and the body-roll alternates. Indeed, a non-propulsive clearing phase follows the end of the propulsive arm movement to prepare the underwater recovery, which results in a single catch-up coordination mode. In the simultaneous strokes (in butterfly; in breaststroke), the key points defining the beginning and end of the stroke phases were analysed and the arm to leg coordination was assessed by four-time gaps, which measure the synchronisation of these key points. The time gaps between key points decreased with increases in stroke rate and/or velocity, indicating better propulsive continuity.

Although these studies demonstrated coordination differences as a function of race pace, skill level and gender, no study has yet focussed on the adaptations in swimming coordination common to the front crawl, backstroke, butterfly and breaststroke. Thus, the aims of this study were (1) to model the relationships among stroke rate, stroke length,
coordination and velocity in the four strokes and (2) to analyse any modelling differences and common changes among them.

2. Material and methods

Forty-eight elite male swimmers voluntarily participated in this study and were assigned to one of four groups (n = 12), with each group representing a stroke specialty. The protocol was fully explained to the participants and they provided written consent to participate in the study, which was approved by the university ethics committee. The main characteristics of the subjects were: for front crawlers: age: 22.4 ± 3.6 years, mass: 78.6 ± 4.8 kg, height: 184.3 ± 4.2 cm, best time on 100-m: 51.3 ± 1.1 s, which represented 94 ± 2% of the long course male world record (WR); for backstrokers: age: 19.6 ± 4.7 years, mass: 74.2 ± 5.3 kg, height: 180.6 ± 5.3 cm, best time on 100-m: 59.4 ± 2.1 s, which represented 90.1 ± 3.1% of WR; for breaststrokers: age: 20 ± 2.5 years, mass: 80.4 ± 6.7 kg, height: 186.7 ± 7.9 cm, best time on 100-m: 65.2 ± 2.3 s; which represented 92.6 ± 2.3% of WR; for butterflyers: age: 20.6 ± 3.7 years, mass: 76.6 ± 7.6 kg, height: 180.7 ± 4.8 cm, best time on 100-m: 57.5 ± 1.4 s; which represented 90.6 ± 2.4% of WR.

The swimmers performed four trials in their specialty at successively increasing speed: the speed of the 400-m, the 200-m, the 100-m and the 50-m events, with a 4-min rest between trials. The trials consisted of swimming at the imposed speed for a distance of only 25 m in order to prevent fatigue effects and allow the focus to remain on motor control adaptations. The trials were self-paced and started in the water without diving. To avoid breathing effects on coordination, the swimmers were instructed not to breathe except in breaststroke. After each trial, all swimmers were informed of their performance time, which was expected to be within ±2.5% of the targeted race speed. If this was not the case, the subject repeated the trial.

A lateral aerial video camera was superposed on a lateral underwater video camera (50 Hz), and they were fixed on the same trolley. The trolley was pulled along the side of the pool by an operator at the same velocity as the swimmers, with each subject’s head being the mark followed by the operator to control parallax. The two cameras were connected to a double-entry audio–visual mixer, a video timer, a video recorder and a monitoring screen to genlock and mix the lateral aerial and underwater views on the same screen. A third camera (50 Hz) video-taped the swimmers from a frontal underwater view and was genlocked and mixed with the lateral underwater view on another screen. From this video device three operators subjectively analysed the key points of arm and leg phases with a precision of 0.02 s and using a blind technique. Last, a fourth camera (50 Hz), genlocked and mixed with the lateral underwater view for time synchronisation, video-taped all trials with a profile view from above the pool. This camera allowed us to measure the time it took for each swimmer’s head to cover a distance of 12.5 m (from the rope line at 10–22.5 m) for the calculation of the average velocity. Two plots delimited the 10-m and 22.5-m points on the right and left sides of the swimming pool.

The stroke rate (SR) was obtained by counting the number of video frames for the three strokes of the 12.5 m from entry of the left hand at cycle 1 to entry of the left hand at cycle 4. Using the average velocity (V) and the SR, the stroke length (SL) could be calculated in m stroke−1: \( SL = V \times SR/60 \).

In the alternating strokes (front crawl and backstroke), the degree of coordination between the two arms was measured by the Index of Coordination (IdC), which is the time gap between the beginning of propulsion at the first right arm stroke and the end of propulsion at the first left arm stroke, and between the beginning of propulsion in the second left arm stroke and the end of propulsion in the first right arm stroke.

In the front crawl, the duration of the propulsive phase was the sum of the pull and push phases and the duration of the non-propulsive phase was the sum of the entry and catch phase and the recovery phase.

In the backstroke, the duration of the propulsive phase was the sum of the pull and push phases and the duration of the non-propulsive phase was the sum of the entry and catch, hand lag, clearing and recovery phases.

The duration of each phase was measured with a precision of 0.02 s. For each trial, the average relative duration of these phases and the IdC was calculated on three strokes and expressed as a percentage of the duration of one arm stroke.

The Index of Coordination (IdC) quantified either a lag time (catch-up coordination mode: IdC < 0%), continuity (opposition coordination mode: IdC > 0%) or overlap (superposition coordination mode: IdC > 0%) between the propulsions of the two arms.

In the simultaneous strokes (butterfly and breaststroke), four time gaps (T1, T2, T3 and T4) measured either a lag time, continuity or superposition between the stroke phases of each pair of motor limbs. Then, the total time gap (TTG), which was defined as the sum of the absolute values of T1, T2, T3 and T4, was used to assess the effectiveness of the global arm to leg coordination.

In the butterfly stroke, the arm stroke was divided into four phases: entry and catch, pull, push and recovery phases; the leg stroke was also composed of four phases: downward phase of the first kick, upward phase of the first kick, downward phase of the second kick, and upward phase of the second kick. Only swimmers with two leg undulations for one arm stroke were studied, so in all cases one leg stroke corresponded to two leg undulations.

T1 from the start of the arms’ catch phase to the start of the legs’ downward phase of the first kick;
T2 from the start of the arms’ pull phase to the start of the legs’ upward phase of the first kick;
T3 from the start of the arms’ push phase to the start of the legs’ downward phase of the second kick;

T4 from the start of the arms’ recovery to the start of the legs’ upward phase of the second kick.

In the breaststroke, the arm stroke was divided into five phases: glide, out sweep, in sweep, first part of the recovery and second part of the recovery; the leg stroke also comprised five phases: propulsion, in sweep, glide, first part of the recovery and second part of the recovery.8

T1 from the end of leg propulsion to the start of arm out sweep;

T2 from the start of arm recovery to the start of leg recovery;

T3 from the end of arm recovery to the end of leg recovery;

T4 from 90° arm flexion in arm recovery to 90° leg flexion in leg recovery.

The duration of each phase was measured for each stroke with a precision of 0.02 s. For each trial, the average relative duration of these phases and of each time gap was calculated on four complete strokes and was expressed as a percentage of the duration of a complete leg stroke.

A normal distribution (the Ryan–Joiner test) and the homogeneity of variance (the Bartlett test) were verified for each variable and allowed parametric statistics.

For each group, one-way ANOVAs tested the pace effect on spatial–temporal and coordinative parameters and were followed by post-hoc Tukey tests. Then, quadratic regression modelled the changes among spatial–temporal parameters (V and SR, V and SL) and between velocity and coordination (V and TTG for simultaneous strokes, V and IdC for alternating strokes). Regressions were plotted for each participant from three strokes swum at each race pace for front crawl and backstroke, and from four strokes swum at each race pace for butterfly and breaststroke. Therefore, after checking that quadratic regression was appropriate for each participant, regressions based on the mean of the 12 participants (Fig. 2 in the electronic version) are presented.

ANCOVA (factor: stroke; co-variable: velocity) assessed the differences among the four strokes with regard to velocity for each variable.

All tests were performed with Minitab 14.10 (Minitab Inc., 2003), with a level of significance set at 0.05.

3. Results

With increased paces, swimmers of each stroke increased V and SR and decreased SL (Table 1 in the electronic version). For each stroke, quadratic linear regressions modelled the increase in SR with V (Fig. 1A in the electronic version) and the decrease in SL with V (Fig. 1B in the electronic version). Regarding the SR changes with increases in velocity, the ANCOVA showed no differences among the four strokes, whereas a significant difference was noted for SL (P < 0.05).

With increased paces, swimmers of each stroke decreased the time gaps (TTG and IdC) between the propulsive phases. Concerning the IdC change with increases in velocity, the ANCOVA showed no differences between the front crawl and backstroke, whereas significant differences were noted between the butterfly and breaststroke for TTG (P < 0.05). In butterfly, the decrease in TTG resulted from the decrease in T2 from the 400-m to the 50-m (P < 0.05; Table 2 in the electronic version), i.e. a decrease in the glide with the arms extended forward. In breaststroke, the decrease in TTG resulted from the decrease in T1 and T3 from the 400-m to the 50-m (P < 0.05, see Table 2 in the electronic version). T1 measured the glide time when the body was completely extended, while T3 measured the time gap between the end of arm recovery and the beginning of leg propulsion.

For each stroke, quadratic linear regressions modelled the increase in TTG with V, and the increase in IdC with V, for the mean of the 12 participants (Fig. 2 in the electronic version) and for each swimmer (Fig. 3 in the electronic version).

4. Discussion

In accordance with Hay’s review,2 the curves of our study showed that in swimming the relationships among SR, SL and V correspond to a quadratic regression. Hay2 also indicated that this model could be generalised to several activities and suggested that changes in stride length, stride frequency and velocity may influence the motor organisation. In our study, the modelling of the spatial–temporal parameters was similar to the coordination modelling, supporting the notion that SR, SL and V may influence swimming coordination. In the front crawl, Craig and Pendergast1 observed an optimal SR/SL ratio, which they suggested should be adopted in competition. Based on this suggestion, Seifert et al.4 showed that increases over critical values of SR (over 50 stroke min−1), V (over 1.80 m s−1), and the SR/SL ratio lead to a qualitative change in arm coordination in the front crawl, notably a switching from catch-up to superposition coordination mode. In a protocol of five successive trials swum at maximal velocity with increasing SR, the arm coordination showed greater disparity between subjects at the slow SR than at high SR.10 In fact, high SR decreased the number of swim options because over 50 stroke min−1, a superposition of the propulsive phases was the main arm coordination mode.10 In the present study, the spatial–temporal parameters also influence the coordination because at the 50-m race pace in front crawl, V was 1.85 m s−1, SR was 49.5 stroke min−1 and IdC (1.7%) reached a superposition mode.

In accordance with previous studies,7–9 the present results in butterfly and breaststroke were similar because the time gaps between the key points of the arm and leg phases decreased with the spatial–temporal parameters, resulting in a shorter glide time. These results support Hay’s suggestion that V, SR and SL may influence coordination.
On the other hand, although quadratic regressions characterised the relationships between SR and V and between SL and V in all strokes, the ANCOVA showed differences in the mean SL and changes in SL with velocity among the four strokes. In line with the findings of Chollet et al.,11 the mean SL was greater for the alternating strokes than for the simultaneous strokes. Moreover, SL decreased with velocity more in breaststroke than in the other strokes because the arm and leg underwater recoveries led to high active drag (according to [8,9]).

A single model common to the four strokes was able to explain the relationship between coordination and velocity: a quadratic regression. For the four strokes, this model demonstrated that with increases in velocity, the time gaps between the key points defining the beginning and end of the stroke phases decreased, which led to decreases in glide times and increases in the continuity between the propulsive phases. On the other hand, when alternating and simultaneous strokes were compared, some shades of difference were also noted.

In the front crawl, the mean IdC on the four race paces was higher than in backstroke (−2.9% vs. −13.2%), resulting in greater continuity between the propulsion of the two arms (i.e. called superposition mode when IdC > 0%). This arm coordination in front crawl could be due to the shoulder rolling that favours long propulsive phases. Moreover, the front crawl swimmers switched from catch-up mode in slow paces to superposition mode in fast paces (according to [4]). This switch in coordination observed in front crawl could also be related to environmental constraints: active and wave drag.12 Using the measure of active drag system, Toussaint and Truijens12 showed a quadratic increase in active drag with V. Moreover, at still higher velocities (>1.5 m s⁻¹), wave drag becomes even greater (wave drag amounts to up to 50% of total drag).12 Thus, similar to ships, the calculation of the “hull speed” for a swimmer with an arbitrary height of 2 m showed a value of 1.77 m s⁻¹.12 The higher increase of the hull speed above 1.77 m s⁻¹ (determined by the wave drag), suggested that above this critical velocity (>1.70–1.80 m s⁻¹), the environmental constraints elicit a superposition coordination of the arms in front crawl.

In backstroke coordination, although a quadratic regression modelled the IdC changes with increases in V, the coordination was always in catch-up mode due to the clearing phase at the end of the push phase and before the aerial recovery. Other factors could explain the catch-up coordination: (1) the limited shoulder flexibility²; (2) a lag time with the hand at the thigh at the end of the push phase⁶; (3) the alternating body-roll.⁵ Coordination operates on a smaller scale in backstroke than in front crawl, inviting the swimmer to increase his V by another way than coordination changes, for example by adopting an optimal SR/SL ratio.

In the simultaneous strokes, the decrease in TTG with V was mostly due to the decrease in the glide with the arms extended (according to [7,8]). However, TTG in butterfly was smaller than in breaststroke and showed a slower decrease with V. The smaller TTG in butterfly was due to: (1) a smaller glide time than in breaststroke and (2) a necessarily high degree of coordination between arms and legs. Indeed, because the body undulates the high and low key points of the legs must be synchronised with the arm key points.⁷ Therefore, in butterfly the time gaps T1, T3 and T4 of the elite swimmers were never more than 4% of the duration of a complete stroke (Table 2 in the electronic version). Conversely, in the breaststroke the TTG was high at slow pace due to a long glide with the body completely extended (near 40% of a stroke).⁸,⁹ This TTG considerably decreased with V, because the swimmers had to increase SR and minimise the glide to compensate the high active drag caused by the underwater recoveries of the arms and legs. Some of the top breaststroke swimmers overlapped two contradictory phases and anticipated the beginning of leg propulsion without waiting for the end of arm recovery (which explained the significant decrease in T3 from the 400-m to the 50-m; Table 2 of the electronic version). Using superposition coordination could be an effective sprint strategy as it increases the mean velocity.⁸,⁹

**Practical implications**

All the swimmers of this study had an elite skill level and were assessed in their stroke specialty. The slight inter-individual differences in the coordination curve shape (Fig. 3 in the electronic version) may have been due to different coaching strategies, specialty of the swimmer or motor organisation. Therefore, some practical applications arise from these inter-individual differences:

1. All swimmers were French and came from four different clubs. In other countries or clubs, coaches may use different monitoring strategies of the SR/SL ratio and to the interest accorded to the coordination flexibility.

2. The longer the coordination curve, the greater the swimmer’s scale of coordination, indicating flexibility in coordination. Indeed, the higher the maximal coordinate and the lower the minimal coordinate of the curve, the more the swimmer is exploring human limits. To the coach, this indicates that swimmers reach different velocity ranges through the type of coordination mode: catch-up mode by using glide time or superposition mode by overlapping the propulsive phases.

3. Most of the swimmers were sprint specialists. However, the profile of the mid-distance specialists could explain why the scale of their spatial–temporal and coordination curves was smaller than that of the sprint specialists. A previous study showed this phenomenon in a comparison of swimmers and triathletes;¹³ because the triathletes usually swim at small scale of velocity (mid- and long-distance paces), they were adapted too overcoming a small scale of active drag and adopted a constant coordination to do this. When velocity increased from long-distance pace to sprint pace, the triathletes...
maintained catch-up coordination mode (IdC between −9.6% and −5.6%) while the swimmers changed to superposition mode. The elite mid-distance swimmers of this study, like the triathletes, may have a small scale of coordination.

(4) Given that drag increases with velocity squared, the relationship between time gaps and velocity should be quadratic and not linear; if the changes are linear, this reflects a miss-adaptation of motor control. Thus, the coach could determine the individual optimal SR/SL ratio to obtain effective coordination for a given velocity. An inappropriate SR/SL ratio could lead to too long a glide time or to ineffective superposition of the propulsions, hence a drop in the velocity.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsams.2008.03.002.

References