Differences in spatial-temporal parameters and arm–leg coordination in butterfly stroke as a function of race pace, skill and gender

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Abstract

Spatial-temporal parameters (velocity, stroke rate, stroke length) and arm–leg coordination in the butterfly stroke were studied as a function of race pace, skill (due to technical level, age, and experience) and gender. Forty swimmers (ten elite men, ten elite women, ten less-skilled men, and ten less-skilled women) performed the butterfly stroke at four velocities corresponding to the appropriate paces for the 400-m, 200-m, 100-m, and 50-m, respectively. Arm and leg stroke phases were identified by video analysis and used to calculate four time gaps ($T_1$: the time difference between the start of the arms’ catch phase and the start of the legs’ downward phase of the first leg kick; $T_2$: the time difference between the start of the arms’ pull phase and the start of the legs’ upward phase of the first leg kick; $T_3$: the time difference between the start of the arms’ push phase and the start of the legs’ downward phase of the second leg kick; and $T_4$: the time difference between the start of the arms’ recovery and the start of the legs’ upward phase of the second leg kick) and the total time gap (TTG), i.e., the sum of the four discrete time gaps. These values described the changing coupling of arm to leg actions over an entire stroke cycle. A significant race pace effect indicated that the synchronization between the key motor points of the arms and legs, which determine the starts and ends of the arm and leg stroke phases, increased with pace for all participants. A significant skill effect indicated that the elite swimmers had greater velocity, stroke length, and stroke rate and stronger synchronization of the arm and leg stroke phases than the less-skilled swimmers, due to smaller $T_2$ and $T_3$ and greater $T_1$. A significant gender effect revealed greater velocity and stroke length for the men, and smaller $T_1$ for the less-skilled women. These time gap differences between skill levels were related to the capacity of elite swimmers to assume a more streamlined position of trunk, head and upper

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limbs during leg actions, adopt a shorter glide and higher stroke rate to overcome great forward resistance, and generate higher forces and use better technique during the arm pull. Thus, coaches are advised to begin monitoring arm–leg coordination earlier in swimmers’ careers to ensure that they attain their highest possible skill levels.

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1. Introduction

Improvement in swimming performance has been explained in terms of better control of stroke rate and stroke length, in particular with regard to race paces (Craig & Pendergast, 1979), skill due to age (Arellano, Sanchez-Molina, Navarro, & De Aymerich, 2003), and gender (Grimston & Hay, 1986; Pai, Hay, & Wilson, 1984). The increase in velocity was predominantly related to an increase in stroke rate, except at the highest velocity where stroke length may somewhat decrease (Craig & Pendergast, 1979). More recently, Chollet, Pelayo, Tourny, and Sidney (1996) found that for men and women alike, velocity, stroke rate and stroke length were greater in the 100-m butterfly than the 200-m. In an analysis of the 100-m in the four strokes that compared skill due to age, Arellano et al. (2003) showed that young swimmers had a lower stroke rate and greater stroke length than older swimmers. The greater length could be explained by the time spent gliding with the arms forward and may be related to the comparatively low strength of younger swimmers (Vorontsov, Binevsky, Filonov, & Korobova, 1999). A positive correlation was found between swim velocity and tethered swimming forces (Sharp, Troup, & Costill, 1982), suggesting that stroke length can be increased by developing forces. However, greater stroke length is not only related to age, but also to gender (Grimston & Hay, 1986; Pai et al., 1984). In front crawl, Grimston and Hay (1986) confirmed that six parameters (axilla, hand and foot cross-sectional areas, leg frontal area, leg and arm lengths) were significantly larger for men than for women and influenced stroke length by 89%, stroke rate by 41%, and velocity by 17%. More globally, the characteristics of women, notably their smaller arm span and height (Pai et al., 1984), and their lower forces and power output (Sharp et al., 1982; Toussaint, Hollander, Van den Berg, & Vorontsov, 2000) have been advanced to explain their smaller stroke length and lower velocity.

Despite the wealth of information provided by these studies, the monitoring of technical, kinetic and spatial-temporal parameters seems insufficient to bring out maximal performance in less-skilled swimmers and to explain gender differences. Indeed, the dynamical systems approach to motor control in humans emphasizes the importance of interlimb coordination (Kelso, 1995). In bimanual coordination, Kelso (1995) showed that in-phase coupling (flexion or extension of the two fingers) is more stable than anti-phase coupling (flexion of one finger coupled to extension of the other finger). When the frequency of finger oscillation (the so-called control parameter) is increased, participants switch from anti-phase to in-phase coordination (Kelso, 1995). In butterfly stroke, this corresponds to a synchronization between the key points determining the starts and
ends of the arm and leg stroke phases, which increases when velocity and stroke rate increase (Chollet, Seifert, Boulesteix, & Carter, 2006). Indeed, recent analyses of arm coordination in front crawl (Chollet, Chalies, & Chatard, 2000) and arm–leg coordination in breaststroke (Chollet, Seifert, Leblanc, Boulesteix, & Carter, 2004) and butterfly (Chollet et al., 2006) confirmed that an improvement in swimming technique often entails more than the correction of common stroke mistakes and a better stroke rate/stroke length ratio for a given velocity. In front crawl, long time gaps between the arms’ propulsive actions, corresponding to catch-up coordination, were observed at slow paces and also characterized less skilfull swimmers (Chollet et al., 2000). With increases in race pace, elite men decreased the time gaps between the arms’ propulsions and switched from catch-up to superposition coordination, whereas less-skilled swimmers (Chollet et al., 2000) and elite women (Seifert, Boulesteix, & Chollet, 2004) maintained catch-up coordination because their slower velocity for the same race pace generated less active drag to overcome, compared to the elite men.

In breaststroke, great active drag arises from the underwater recoveries and high coupling between arm and leg movements is an efficient response to drag (Chollet et al., 2004). Thus, with increases in race pace, elite breaststroke swimmers decrease the time gaps between the key points determining the starts and ends of the arm and leg stroke phases in order to maximize propulsive continuity between the arm and leg actions (Chollet et al., 2004). These changes are less effective in less-skilled swimmers (Leblanc, Seifert, Baudry, & Chollet, 2005), who show great time gaps between the arm and leg recoveries, and in elite women (Seifert & Chollet, 2005), who have longer glide times than elite men.

In butterfly, the aerial recovery of the arms is facilitated by the leg undulation, but to be effective the kick should appear as a consequence of a body wave-like cefalo-caudal undulation motion (Sanders, Cappaert, & Devlin, 1995). These authors showed specific frequency, amplitude and phase characteristics in the leg oscillations (kick) that lead to a body wave-like motion and possibly conserve mechanical energy; hence the arm and leg actions need to be highly coordinated. Maglischo (2003) thus emphasized that: (1) the downward phase of the first leg undulation should occur during the catch phase of the arms, and (2) the upward phase of the second undulation should occur during the push phase of the arms. However, this author did not quantify the degree of arm–leg coordination and thus could not fully explain how high velocity is realized. Using four time gaps to analyze the arm–leg coordination, Chollet et al. (2006) recently showed that, whatever the race pace, most of the time gaps of elite butterfly swimmers were close to 5%, revealing a high degree of synchronization between the key points determining the starts and ends of the arm and leg stroke phases. They further showed that the glide time decreased to 0% with increases in pace.

In the simultaneous strokes (breaststroke and butterfly stroke), a high degree of arm–leg coordination ensures the propulsive continuity between the arm and leg actions (Chollet et al., 2004; Seifert & Chollet, 2005) and induces fewer instantaneous fluctuations in velocity (Mason, Tong, & Richards, 1992; Sanders, 1996). Craig and Pendergast (1979) showed that front and back crawl are characterized by fewer instantaneous velocity fluctuations (15–20%) than the simultaneous strokes (45–50%), which underscores the need to minimize them in butterfly. Indeed, Barbosa et al. (2005) showed that high fluctuations generate early fatigue in butterfly. Therefore, a high degree of motor control in the breaststroke and butterfly, which depends on the ability to decrease the time gaps between the arm and leg phase key points, notably by monitoring glide times, should favor propulsive
continuity, increase propulsive times (Chollet et al., 2004, 2006; Seifert & Chollet, 2005) and decrease instantaneous velocity fluctuations.

Although a profile of expert coordination in butterfly has emerged from these studies, little is known about the coordination used by less-skilled swimmers who, because of their poorer technique and smaller forces due to younger age, lack the experience of elite swimmers. It would indeed be interesting to investigate how these less-skilled swimmers organize their arm–leg coordination in the butterfly stroke. Similarly, gender was found to influence glide time in front crawl (Seifert et al., 2004) and breaststroke (Seifert & Chollet, 2005), with longer glide times characterizing female coordination, which highlights the interest of examining its influence in butterfly coordination.

The aim of this study was to examine and compare arm–leg coordination in elite and less-skilled swimmers of both genders during butterfly performance of increasing race pace. We hypothesized that (i) increases in race pace, (ii) higher skill, and (iii) gender (men rather than women) would all contribute to a higher degree of arm–leg coordination (i.e., shorter time gaps between the key points determining the starts and ends of the arm and leg stroke phases) and thus longer relative propulsive times.

2. Material and methods

2.1. Participants

Forty swimmers voluntarily participated in this study, and formed four groups of 10 swimmers as regards skill and gender. The criteria to define each group were based on three factors: (i) skill level: skill level was assessed by the current best time on the 100-m butterfly performed in competition, expressed as percentage of the current world record (% WR) for the 100-m butterfly. The skill level of the elite swimmers ranged from 90% to 100% of WR, which qualified them as either national finalists or international competitors, while the skill level of the less-skilled swimmers was less than 80% of WR; (ii) age: the elite swimmers were senior swimmers (18–27 years), while the younger/less-skilled swimmers were junior swimmers (15–18 years); (iii) experience: elite swimmers had been swimming for 9–17 years, while the less experienced/less-skilled swimmers had been swimming for 4–8 years. Moreover, the elite swimmers trained 9–10 h per week, while the less-skilled swimmers trained 6–8 h per week. Finally, the lower skillfulness of the less-skilled groups was attributed to their technical level, age and experience, all of which prevented them from attaining international or national finalist rank. Therefore, older swimmers with a poor skill level were not included in our study, and the less-skilled groups were composed mainly of junior swimmers showing strong promise of developing into expert competitors.

Their main characteristics are presented in Table 1. 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. In the case of minors, informed written consent was obtained from the participants and their parents.

2.2. Swim trials

The swimmers performed four butterfly trials at successively increasing velocity in a 25-m pool. Each trial required an individually imposed swim pace corresponding to a specific
Table 1
Characteristics of the four groups

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (year)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Arm span (cm)</th>
<th>Time on 100 m (s)</th>
<th>Skill (% of WR)</th>
<th>Practice (year)</th>
<th>Training (year week⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elite men</td>
<td>20.3 ± 4.3</td>
<td>180.7 ± 5.4</td>
<td>73.3 ± 8.5</td>
<td>189.2 ± 4.0</td>
<td>57.2 ± 1.4</td>
<td>90.9 ± 2.6</td>
<td>11.1 ± 4.4</td>
<td>9.9 ± 2.4</td>
</tr>
<tr>
<td>Less-skilled men</td>
<td>15.7 ± 1.6</td>
<td>179.6 ± 4.1</td>
<td>70.7 ± 7.2</td>
<td>192.8 ± 4.5</td>
<td>66.2 ± 4.3</td>
<td>78.0 ± 5.1</td>
<td>5.3 ± 1.3</td>
<td>8.0 ± 1.4</td>
</tr>
<tr>
<td>Elite women</td>
<td>20.8 ± 4.3</td>
<td>171.0 ± 2.1</td>
<td>59.3 ± 3.2</td>
<td>174.0 ± 2.7</td>
<td>64.5 ± 2.2</td>
<td>90.1 ± 3.3</td>
<td>10.9 ± 3.7</td>
<td>9.8 ± 1.6</td>
</tr>
<tr>
<td>Less-skilled women</td>
<td>17.0 ± 2.2</td>
<td>168.8 ± 4.7</td>
<td>59.6 ± 4.8</td>
<td>171.4 ± 4.2</td>
<td>74.4 ± 4.5</td>
<td>77.0 ± 4.5</td>
<td>7.4 ± 1.8</td>
<td>6.4 ± 1.2</td>
</tr>
</tbody>
</table>

WR: World record.
race or training distance (Chollet et al., 2006): 400-m (V400), 200-m (V200), 100-m (V100), and 50-m (V50) with a rest of 4 min between trials. We therefore distinguished between ‘pace’, which was the target velocity for each swimmer, and ‘velocity’, which was what the swimmer in fact achieved. The trials consisted of swimming at the imposed pace only for a distance of 25 m in order to prevent fatigue effects and thereby allow the focus to remain on motor control adaptations. After each trial, all swimmers were informed of their performance time, which was expected to be within ±2.5% of the targeted race velocity. If this was not the case, the participant repeated the trial.

2.3. Video analysis

An aerial lateral video camera (C1) was superposed on an underwater lateral video camera (C2) (50 Hz, Sony compact FCB-EX10L) (Fig. 1). Both had rapid shutter velocity (1/1000 s) and 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 participant’s head being the mark followed by the operator to control parallax. The two cameras were connected to a double-entry audio–visual mixer (Videonics MX-1), a video timer, a video recorder and a monitoring screen to genlock and mix the lateral underwater and aerial views on the same screen. A third camera (C3) (50 Hz, Sony compact FCB-EX10L) videotaped the swimmers from a frontal underwater view (Fig. 1) and was genlocked and mixed with the underwater lateral view on another screen. From this video device, three operators analyzed the key points determining the starts and ends of the arm and leg stroke phases. The precision of this technique was 0.02 s and the operators used a blind technique. The three analyses were compared only when each operator had completed his own analysis. When the difference between the three analyses did not exceed an error of 0.04 s, the mean was accepted to validate the key point of each phase. When the error exceeded 0.04 s, the three operators together proceeded to a new assessment of the phase key points.

![Fig. 1. Locations of cameras around the pool and the swimmer: C1 is the underwater lateral camera fixed on the trolley; C2 is the aerial lateral camera fixed on the trolley; C3 is the underwater frontal camera; C4 is the aerial lateral camera placed above the pool.](image-url)
Last, a fourth camera (C4) (50 Hz, Panasonic NV-MS1 HQ S-VHS), genlocked and mixed with the lateral underwater view for time synchronization (Fig. 1), videotaped all trials with a profile view from above the pool. This camera allowed us to measure the time it took for each swimmer to cover a distance of 12.5 m (from 10 m to 22.5 m) for the calculation of the average velocity and the stroke rate. Two plots delimited the 10-m and 22.5-m points on the right and left sides of the pool (Fig. 1). When the head of the swimmer reached the rope line at 10 m, time was recorded until the head reached the line at 22.5 m. The duration of one complete stroke was from the left hand entry at stroke 1 to the left hand entry at stroke 2 and stroke rate was obtained by counting the requisite number of video frames for the four strokes of the 12.5 m. Using the average velocity and the stroke rate, the stroke length could be calculated: stroke length = (velocity × stroke rate)/60.

2.4. Arm and leg stroke phases

As shown in Fig. 2, the key points of the arm were used to determine the starts and ends of the four phases that compose an arm stroke (Chollet et al., 2006):

(1) Entry and catch of the hands in the water, which corresponds to the time between the entry of the hands into the water and the beginning of their backward movement; (2) Pull phase, which corresponds to the time between the beginning of the backward movement of the hands and their entry into the plane vertical to the shoulders; (3) Push phase, which corresponds to the time between the positioning of the hands below the shoulders and their exit from the water. The pull and the push phases correspond to the arm propulsive time; and (4) Recovery phase, which corresponds to the time between the exit of the hands from the water and their subsequent entry into the water.

Four arm strokes were analyzed in the 12.5-m zone after which the results were averaged. The duration of each phase was measured for each stroke with a precision of 0.02 s and was expressed as percentage of the duration of a complete arm stroke.

As shown in Fig. 2, the key points of the legs were used to determine the starts and ends of the four phases that compose a leg stroke (Chollet et al., 2006). One leg stroke corresponded to two leg kicks and one leg kick comprised one downward phase and one upward phase. Only swimmers with two body undulations/leg kick for one arm stroke were studied. The four phases were:

(1) Downward phase 1, which corresponds to the time between the high and low break-even points of the feet during the first kick; (2) Upward phase 1, which corresponds to the time between the low and high break-even points of the feet during the first kick; (3) Downward phase 2, which corresponds to the time between the high and low break-even points of the feet during the second kick; and (4) Upward phase 2, which corresponds to the time between the low and high break-even points of the feet during the second kick. The duration of each phase was measured for each stroke with a precision of 0.02 s and was expressed as percentage of the duration of a complete leg stroke.

2.5. Arm–leg coordination

Four time gaps were identified (Chollet et al., 2006; Fig. 2): T1 is the time difference between the start of the arms’ catch phase and the start of the legs’ downward phase of the first leg kick; T2 is the time difference between the start of the arms’ pull phase and
the start of the legs’ upward phase of the first leg kick; \( T_3 \) is the time difference between the start of the arms’ push phase and the start of the legs’ downward phase of the second leg kick; \( T_4 \) is the time difference between the start of the arms’ recovery and the start of the legs’ upward phase of the second leg kick. The \textit{total time gap} (TTG) was defined as the sum of the absolute values of \( T_1, T_2, T_3 \) and \( T_4 \), and was used to assess the effectiveness of the global arm–leg coordination. In all trials, the time gaps and TTG were expressed as the percentage of a complete stroke.

2.6. Statistical analysis

A normal distribution (Ryan–Joiner test) and the homogeneity of variance (Bartlett test) were verified for each variable and allowed parametric statistics. Two-way ANOVAs (Skill \( \times \) Gender), completed by post-hoc Tukey tests, analyzed the differences in characteristics between groups. Three-way ANOVAs (Pace \( \times \) Skill \( \times \) Gender) analyzed the main effects and the possible interactions between the main effects (Table 2) and were completed by post-hoc Tukey tests. All tests were performed with Minitab 14.10 (Minitab Inc., 2003), with a level of significance set at \( p < .05 \).
Table 2
Results of three-way ANOVAs for each variable, with a level of significance set at $p < .05$

<table>
<thead>
<tr>
<th>Variables</th>
<th>Pace</th>
<th>Skill</th>
<th>Gender</th>
<th>Pace $\times$ Skill</th>
<th>Pace $\times$ Gender</th>
<th>Skill $\times$ Gender</th>
<th>Pace $\times$ Skill $\times$ Gender</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>$F(3, 144) = 42.79$</td>
<td>$F(1, 144) = 64.07$</td>
<td>$F(1, 144) = 115.64$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>$F(3, 144) = 7.9$</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .0001$</td>
<td>$p = .0001$</td>
<td>$p = .0001$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke rate</td>
<td>$F(3, 144) = 49.56$</td>
<td>$F(1, 144) = 4.94$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .0001$</td>
<td>$p = .028$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke length</td>
<td>$F(3, 144) = 12.12$</td>
<td>$F(1, 144) = 4.78$</td>
<td>$F(1, 144) = 67.63$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>$F(3, 144) = 4.31$</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .0001$</td>
<td>$p = .03$</td>
<td>$p = .0001$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_1$</td>
<td>$F(3, 144) = 5.96$</td>
<td>$F(1, 144) = 7.48$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .001$</td>
<td>$p = .007$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_2$</td>
<td>$F(3, 144) = 12.73$</td>
<td>$F(1, 144) = 45.11$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .0001$</td>
<td>$p = .0001$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_3$</td>
<td>n.s.</td>
<td>$F(1, 144) = 51.17$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p = .0001$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_4$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td>Total time gap</td>
<td>$F(3, 144) = 9.63$</td>
<td>$F(1, 144) = 58.36$</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
<td>n.s.</td>
</tr>
<tr>
<td></td>
<td>$p = .0001$</td>
<td>$p = .0001$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

n.s. – non significant.
3. Results

3.1. Participant characteristics

For each gender, the elite groups were older than the less-skilled swimmers, $F(1,36) = 15.96, p < .05$, and had greater experience (difference in years of practice: $F(1,36) = 22.87, p < .05$; difference in hours of training per week: $F(1,36) = 24.1, p < .05$) and a higher skill level, $F(1,36) = 96.15, p < .05$, as evidenced by their faster times on a 100-m butterfly, $F(1,36) = 77.83, p < .05$ (Table 1). The men were heavier, $F(1,36) = 39.81, p < .05$, and taller, $F(1,36) = 58.54, p < .05$, had a greater arm span, $F(1,36) = 217.94, p < .05$, and swam faster than the women, $F(1,36) = 52.53, p < .05$, but the elite groups of both genders had a high level of expertise (Table 1).

3.2. Pace effect

With increased pace, all groups increased velocity and stroke rate, and decreased stroke length and TTG, due to the decreases in $T1$ and $T2$ (Table 3 and Fig. 3).

3.3. Skill effect

Velocity and stroke length were higher in the elite groups than in the less-skilled groups (Table 4). Stroke rate was higher in the elite men than in the less-skilled men (Table 4). Elite swimmers showed a smaller total time gap (TTG) than the less-skilled groups (Fig. 4), suggesting higher global synchronization between the key points determining the starts and ends of the arm and leg stroke phases. Indeed, less-skilled swimmers had greater $T2$ than the elite swimmers (Fig. 4), indicating a lag time between the start of the arms’ pull phase and the start of the legs’ upward phase (i.e., a lack of continuity between the propulsion of the two motor limbs). Less-skilled swimmers also had greater $T3$ than elite swimmers (Fig. 4), showing that the propulsions of the arms (push phase) and legs (downward phase of the second leg kick) did not start simultaneously.

3.4. Gender effect

The women had lower velocity and smaller stroke length than the men (Table 4). The less-skilled women had smaller $T1$ than the less-skilled men (Fig. 4) due to some negative

<table>
<thead>
<tr>
<th>Swim paces</th>
<th>Velocity (m s$^{-1}$)</th>
<th>Stroke rate (stroke min$^{-1}$)</th>
<th>Stroke length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-m</td>
<td>1.32 ± 0.14</td>
<td>38.5 ± 5.1</td>
<td>2.07 ± 0.25</td>
</tr>
<tr>
<td>200-m</td>
<td>1.4 ± 0.15$^a$</td>
<td>42 ± 5.2$^a$</td>
<td>2.02 ± 0.24</td>
</tr>
<tr>
<td>100-m</td>
<td>1.5 ± 0.15$^{a,c}$</td>
<td>47.8 ± 5.3$^{a,c}$</td>
<td>1.9 ± 0.22$^{a,c}$</td>
</tr>
<tr>
<td>50-m</td>
<td>1.56 ± 0.15$^{a,b,c}$</td>
<td>51.7 ± 5.4$^{a,c,b}$</td>
<td>1.82 ± 0.25$^{c,b}$</td>
</tr>
</tbody>
</table>

$^a$ Significant difference with preceding pace.

$^b$ Significant difference with the 200-m, $p < .05$.

$^c$ Significant difference with the 400-m, $p < .05$.  

Table 3
Results of post-hoc Tukey tests comparing spatial-temporal parameters between paces on the mean of the four groups
values (standard deviation of $T1 = 3.4\%$, as regards mean of $T1 = 1\%$, showed negative values of some participants), indicating that the legs began their propulsion (downward phase of the first leg kick) before the arms had entered the water.

Fig. 3. Results of post-hoc Tukey tests comparing coordination variables between paces on the mean of the four groups (a) significant difference with the 200-m, (b) significant difference with the 400-m, $p < .05$: $T1$ is the time difference between the start of the arms’ catch phase and the start of the legs’ downward phase of the first leg kick; $T2$ is the time difference between the start of the arms’ pull phase and the start of the legs’ upward phase of the first leg kick; $T3$ is the time difference between the start of the arms’ push phase and the start of the legs’ downward phase of the second leg kick; $T4$ is the time difference between the start of the arms’ recovery and the start of the legs’ upward phase of the second leg kick. All time gaps are expressed in % of a complete stroke.

Table 4
Results post-hoc Tukey tests comparing spatial-temporal parameters between gender and skill on the mean of the four swim paces

<table>
<thead>
<tr>
<th>Groups</th>
<th>Velocity (m s$^{-1}$)</th>
<th>Stroke rate (stroke min$^{-1}$)</th>
<th>Stroke Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elite male</td>
<td>1.62 ± 0.14</td>
<td>47 ± 6.1</td>
<td>2.09 ± 0.15</td>
</tr>
<tr>
<td>Less-skilled male</td>
<td>1.44 ± 0.14$^{a}$</td>
<td>42.5 ± 7.2$^{a}$</td>
<td>2.08 ± 0.29</td>
</tr>
<tr>
<td>Elite female</td>
<td>1.4 ± 0.12$^{a,c}$</td>
<td>44.9 ± 6.6</td>
<td>1.89 ± 0.17$^{a,c}$</td>
</tr>
<tr>
<td>Less-skilled female</td>
<td>1.31 ± 0.14$^{a,b,c}$</td>
<td>45.7 ± 7.3</td>
<td>1.76 ± 0.21$^{a,c,b}$</td>
</tr>
</tbody>
</table>

$^{a}$ Significant difference with preceding group.

$^{b}$ Significant difference with less-skilled male.

$^{c}$ Significant difference with elite male, $p < .05$. 
4. Discussion

4.1. Pace effect

The hypothesis was confirmed: increase in race pace led to a higher degree of coordination in butterfly because the time gaps between the arm and leg phases decreased. Indeed, for the four groups, the increases in race pace led to decreases in TTG (the sum of the absolute values of the four time gaps) of 64–75.4%; in $T_1$, of 14.7–45.6%; and in $T_2$, of 51.3–62.4%. In agreement with previous studies of front crawl (Chollet et al., 2000; Seifert et al., 2004), breaststroke (Chollet et al., 2004; Seifert & Chollet, 2005) and butterfly (Chollet et al., 2006), these results indicate a global change in arm–leg coordination (measured by TTG), which was due to the decrease in the time spent in the glide with the arms extended forward (measured by $T_1$) and to a decrease in the glide time between the propulsion of the two motor limbs (measured by $T_2$). This interlimb organization can be explained from both biomechanical and motor control perspectives. First, having a glide time with the arms extended forward at the top of the stroke is a strategy to conserve oxygen required by longer swims, because the head, trunk and upper limbs are profiled in...
streamlined position to glide (Colwin, 2002) and thus provide an instant of rest at each stroke on a long butterfly swim. Second, it is easier, in terms of coordination, to alternate arm actions with leg actions (called ‘out-of-phase’ mode in the dynamical systems approach) and to have a variable glide time between the two limb actions, but it is not effective for reaching sprint paces, where high synchronization of the arm and leg key points of the stroke phases was observed (called ‘in-phase’ mode in the dynamical systems approach) (Chollet et al., 2006). The transition from out-of-phase to in-phase mode of arm–leg coordination in sprint was concomitant to the increase in stroke rate, suggesting that this parameter was also a control parameter of coordination. Potdevin, Bril, Sidney, and Pelayo (2006) have already shown that stroke rate is the main control parameter of inter-arm coordination in front crawl, confirming the results observed using the dynamical systems approach to bimanual coordination (Kelso, 1995).

4.2. Skill effect

The hypothesis was accepted because smaller time gaps were observed for the higher skill level swimmers of both genders.

4.2.1. Time gap 1

According to Chollet et al. (2006), the smaller the time gap, the better the coordination. \( T_1 \) close to 0% should thus indicate better arm to leg synchronization in the less-skilled women than in the elite women, but this was not the case. In fact, the low mean \( T_1 \) of the less-skilled women was due to the negative values \((-4 < T_1 < 0)\) of four participants, i.e., nearly 16 strokes. This coordination was suboptimal because, although the legs were propelling, the arms and hands were not streamlined in an extended position to prepare for the catch (Colwin, 2002). This downward kick is the strongest in the stroke (Hahn & Krug, 1992) and should occur soon after the arm entry (Colwin, 2002). Unlike the less-skilled women, in the three other groups only one swimmer of the less-skilled men had negative \( T_1 \); this time gap ranged from \(-2\%\) to 0%.

4.2.2. Time gap 2

For all paces, the glide time between the propulsion of the two motor limbs (assessed by \( T_2 \)) was 52.2–65% smaller for elite men than for less-skilled men and 58.7–71.6% smaller for elite women than for less-skilled women. The lack of synchronization observed at the hand entry (\( T_1 \)) for the less-skilled swimmers persisted because these swimmers tended to decompose the stroke. As previously noted for long swims corresponding to slow paces, it is easier in terms of coordination to alternate arm actions with leg actions (out-of-phase coordination mode) and to have a variable glide time between the two limb actions (Chollet et al., 2006). Some animals that swim underwater such as giant cormorants (Ribak, Weihis, & Arad, 2005), penguins (Van Dam, Ponganis, Ponganis, Levenson, & Marshall, 2002), and dolphins (Williams, Haun, & Friedl, 1999) improve their metabolic efficiency of swimming by using a locomotion pattern that alternates periods of propulsion and gliding. This benefits air-breathing animals because the reduced oxygen utilization allows for a longer dive. We can hypothesize that the less-skilled swimmers, who used the longer glide phase coordination pattern, adopted a burst-and-glide strategy to conserve oxygen, but this is not a sound biomechanical strategy to achieve high velocities (Barbosa et al., 2005; Mason et al., 1992). Indeed, during their longer glide times, the less-skilled swimmers...
lost the velocity reached in the preceding propulsive phase and thus showed great instantaneous velocity fluctuations (Mason et al., 1992), which are known to generate early fatigue (Barbosa et al., 2005).

4.2.3. Time gap 3

The lower synchronization of the less-skilled swimmers persisted in $T_3$. Whereas $T_3$ of the elite swimmers was close to 0% (from $-5.1\%$ to $-1.8\%$), i.e., high synchronization between the beginning of the arm push phase and the beginning of the downward leg movement, the less-skilled swimmers had a time gap near 10% (Fig. 4), which disturbed propulsion. Schleihauf et al. (1988) noted that, as in front crawl, the highest effective propulsive forces occur near the end of the arm pull in butterfly (near 125 N for a 100-m race pace). Thus, it is important to aim for perfect timing between the push phase of the arms and the downward kick of the legs (Sanders, 1996) because this superposition of the two propulsive phases provides the highest body acceleration in the stroke (Mason et al., 1992). Conversely, a lack of coordination means large instantaneous velocity fluctuations that are detrimental to propulsion (Hahn & Krug, 1992). Two hypotheses could explain the coordination of the less-skilled swimmers. First, regarding strength, Vorontsov et al. (1999) showed that the strongest effect of growth has been found for girls of 13–15 and boys of 14–15 years of age. Even though our less-skilled swimmer groups were slightly older (16–17 years), based on the findings of these previous authors we hypothesized that less-skilled swimmers would apply less force at the end of the arm pull than elite swimmers of 20 years, which could explain their poorer coordination at $T_3$. Their poorer coordination corresponded to lateness in arm propulsion with regard to the leg action, i.e., the hands passed below the shoulders after the beginning of the downward kick. The second hypothesis related to anticipation and depreciation in amplitude of the second kick, which could modify the time spent in undulation, and therefore the synchronization between the second downward kick and the push phase of the arms.

4.3. Gender effect

The hypothesis was partially accepted because the differences in coordination were small (they only concerned $T_1$ for the less-skilled swimmers), whereas the differences in the spatial-temporal parameters were greater between genders.

The arm–leg coordination of the less-skilled women was ineffective because the arms were not in a streamlined position (extended forward) and caused active drag when the legs began propulsion. Therefore, these women tended to compensate their lack of coordination by adopting a higher stroke rate, but this strategy disturbed their motor organization, instead of improving the coupling of the two motor limbs, as proposed by the dynamical systems approach (Kelso, 1995).

For the elite swimmers, the gender differences could be related to biomechanics, notably because the higher velocity of the men for the same race pace as the women meant that they had to overcome higher active drag. The higher forces and power output regularly observed in men enabled them to develop greater stroke length and velocity than the women (Sharp et al., 1982; Toussaint et al., 2000). Indeed, Kolmogorov, Rumyantseva, Gordon, and Cappaert (1997) showed that the active drag in butterfly greatly increases over 1.5 m s$^{-1}$, especially for men. This suggests the great propulsive forces that elite swimmers need to apply in order to move forward. Indeed, from 1 to 1.55 m s$^{-1}$, the active
drag of men ranges from 20 to 60 N, as for the women, but over 1.55 m s\(^{-1}\), it increases considerably and approaches 100 N at 1.75 m s\(^{-1}\) (Kolmogorov et al., 1997).

5. Conclusion and practical applications

A significant race pace effect indicated that the synchronization between the key points of the arm and leg phases increased with pace, velocity and stroke rate for the whole population. A significant skill effect confirmed that the elite swimmers had more synchronized arm and leg stroke phases than the less-skilled swimmers, due to smaller \(T_2\) and \(T_3\) in the elite men and greater \(T_1\) and smaller \(T_2\) and \(T_3\) in the elite women. A significant gender effect concerned the difference in \(T_1\) between less-skilled men and women. These differences in time gaps between skill levels and genders were respectively related to the capacity of elite swimmers and male swimmers to assume a more streamlined position of trunk, head and upper limbs during leg actions, to adopt the shorter glide and higher stroke rate needed to overcome great forward drag, and to generate higher forces and use better technique during the arm pull. Therefore, coaches could encourage their swimmers to use fast coordination strategies (i.e., with small time gaps), rather than allowing them to use the gliding strategies that some authors seem to believe promote the oxygen conservation required by longer swims. Moreover, training with the glide reinforces this motor behavior and probably impairs swimmers’ attempts to swim faster in competition. We recommend that coaches begin monitoring arm–leg coordination earlier in the swimming career to ensure that less-skilled swimmers reach the highest possible skill level by improving inter-segmental coordination.

References


